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DEVELOPMENT OF iFAB (INSTANT FOUNDRY ADAPTIVE THROUGH BITS) MANUFACTURING PROCESS AND MACHINE LIBRARY

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Final Report

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14. ABSTRACT
This report summarizes work performed under AFRL Contract Number FA8650-11-C-7142 for the development of an iFAB process and machine capability library. Specifically, the report is in draft form and addresses three major task areas relevant to the proposed effort.
The main objective of this research is to create and validate adaptable software libraries of manufacturing processes, machines, tooling and fixtures, and other operations pertinent to the fabrication of electro-mechanical components and/or assemblies for armed military ground vehicles. These libraries will serve as repositories of manufacturing process, machine, tooling, fixture, inspection capability models and associated data for use by the iFAB "foundry" (re)configuration environment.

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Abstract

This report contains deliverables for work performed in the development of an iFAB manufacturing process and machine capability library. Specifically, the report documents work by the performing team in three major task areas relevant to the proposed effort. To satisfy the Task 1 requirements, typical manufacturing operations used in the construction of wheeled military vehicles were reviewed. Within Task 2, characterization (or modeling) of seven specific classes of manufacturing processes and associated machines is provided. Progress with respect to Task 3 (to design and develop the Manufacturing Capability Modeling Environment -MaCME- and M-Libraries) is summarized with software provided as a separate submission.

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1.0 Executive Summary

A digital library containing the key characteristics and production capabilities of a wide range of manufacturing processes and associated resources such as machines, tools, operators, and facilities has been developed. The library, known as the M-Library, and the associated modeling environment, known as the Manufacturing Capability Modeling Environment (MACME), support automated process selection in foundry-style manufacturing of military ground vehicles. A Manufacturing Systems Modeling Language (M-SysML) has been developed to model the various manufacturing concepts involved. A complex knowledge graph-based approach is used to represent the relevant manufacturing knowledge of six major classes of manufacturing processes including material removal, metal forming, polymer and composite manufacturing, additive manufacturing, joining (welding), assembly (mechanical fastening), and finishing processes. The library is validated using several realistic test cases.

2.0 Introduction

This report summarizes work performed under AFRL Contract Number FA8650-11-C-7142 for the development of an iFAB manufacturing process and machine capability library designed to support automated process planning and manufacturability assessment feedback for design. Specifically, the report addresses three major task areas relevant to the proposed effort.

The main objective of this research is to create and validate adaptable software libraries of manufacturing processes, machines, tooling and fixtures, and other operations pertinent to the fabrication of electro-mechanical components and/or assemblies for armed military ground vehicles. These libraries will serve as repositories of manufacturing process, machine, tooling, fixture, inspection capability models and associated data for use by the iFAB "foundry" (re)configuration environment.

The manufacturing process and machine capabilities addressed in this program include the following: 1) relevant conventional and unconventional machining processes and machines, 2) relevant metal forming processes and machines, 3) relevant additive manufacturing processes and machines, 4) relevant joining processes and equipment, 5) relevant assembly processes and equipment, 6) relevant polymer/composites molding processes and equipment, and 7) relevant finishing processes and equipment.

The Manufacturing Systems Modeling Language (M-SysML) is a manufacturing-specific extension to the Systems Modeling Language (SysML) standard, and is developed to build the systems modeling environment (*MaCME)* and the associated tools and algorithms needed to model, store, analyze and synthesize manufacturing capability and process model information. The manufacturing model library created using M-SysML is referred to in the report as the M-Library. Simple process planning use cases are employed to validate and demonstrate library usage.

3.0 Approach

The basic approach used to architect and build the M-Library and MACME is briefly described in this section.

The approach consisted of the following major steps:

1) Reviewing commonly used materials, components and associated manufacturing processes for military ground vehicles.

2) Using a taxonomical approach to model each class of manufacturing processes, tools, and machines.

3) Using a schema-based (or attribute-based) method for modeling the key characteristics and capabilities of each manufacturing process, machine, and tool.

4) Developing a part feature taxonomy that captures the typical shapes/geometry of military vehicle components.

5) Using a process-feature mapping to relate the features in the feature taxonomy to processes and/or tools capable of producing them.

6) Identifying and implementing simple time and cost models for some of the unit processes modeled in the M-Library.

7) Using the OMG Systems Modeling Language (SysML) international standard to develop the manufacturing-domain specific Manufacturing Systems Modeling Language (M-SysML), which is used to represent the semantic knowledge associated with each manufacturing process and resource and relationships between them. The M-SysML is essentially a large, complex knowledge graph.

8) Building a web-dashboard to enable interactive browsing, visualizing, populating and querying the M-Library. The dashboard permits both schema-based and instance-based queries.

9) Building the capability to query the M-Library programmatically using an Application Programming Interface (API).

10) Validating the M-Library with test cases derived from military vehicle designs.

Detailed descriptions of the above steps and the associated results are presented in the following section.

4. 0 Results

This section is organized as follows. The work done in the three major task areas (and their subtasks) addressed by the Georgia Tech iFAB team in their iFAB proposal are described. The emphasis is on the basic approach followed supported by typical examples of the approach and/or its implementation. In some instances, detailed supporting information is included in the Appendix at the end of the report.

4.1 Task 1: Review of Military Ground Vehicle Design, Materials, and Processes (Primary Organization Responsible: GTRI-ATAS, Lead: V. Camp)

The major focus of Task 1 was to assist the Task 2 (process modeling) team in: 1) identifying the relevant manufacturing processes and materials commonly used in the design and fabrication of military ground vehicles, and 2) developing, extending and refining the feature/shape classification system (or taxonomy) for use in process-feature mapping. The process schemas making up the M-SysML-based knowledge graph contained in the M-Library need to contain such mapping in order to permit part-process matching during library use. While the emphasis of the Task 1 team effort on feature/shape classification was on material removal processes, the concepts developed were found to be applicable to other manufacturing processes (e.g. forming). The specific extensions of the feature/shape classification system relevant to material removal processes are presented in the Task 2a portion of this report.

The results of Task 1 are presented in the following sections.

Process and Component Matrix

In order to support iFAB developments at Georgia Tech, a high level description of processes related to military ground vehicles was developed. The utility of this list became evident to various iFAB teams and this list was further developed into a comprehensive list including materials, finishes, manufacturing operations, and assembly techniques among other items. Finally, the list was expanded to include several subsystems in a military vehicle and then updated to indicate which characteristics would be candidates for the various parts or subsystems of a vehicle.

To provide a more concise representation of the large matrix that was previously described, two tables were generated to capture the information on the two axes of the two dimensional matrix. The first table (1.1) lists a number of characteristics that are encountered in the manufacture of military vehicles. The actual matrix does include the mapping between vehicle components and subsystems and candidate operations or characteristics. Table 1.2 lists the system level breakdown for typical military ground vehicles. Furthermore, these lists are not considered comprehensive, but representative of major activities associated with ground based military vehicles.

Note that the complete tables have been already provided to DARPA and posted on the iFAB Sharepoint site.

iFAB Library Utilization Example

In building a process and material library for iFAB, it became evident that an understanding of how the designer and/or process planner may interact with these libraries would impact the content or parameters needed in the libraries. To better understand this relationship, an example problem was generated to highlight how the libraries and the designer/process planner could interact. The goal of this exercise became how the designer/process planner would take information from fabrication drawings and input it into a system that could then utilize the iFAB libraries. The implicit goal of the exercise was to take a large number of potential processes and provide a way to reduce the number of candidate operations in order to lessen the load on computationally intensive exercises such as algorithms to minimize cost and schedule.

The following list of items was assumed to be known to the user of the library, presumably obtained from the META encoded design flowed down to iFAB.

- ***Part geometry***: solid model or engineering drawings including overall part dimensions
- ***Part features***: for the time being it is assumed that the process planner manually (or with the help of automatic feature recognition software) has parsed the solid model of the part to identify the features to be produced.
- ***Material*** *part is made from*: specific material and potentially the shape of available raw stock.
- ***Tolerance*** *for part features (includes location, form, and dimensional tolerance) (where applicable)*
- ***Surface roughness*** *specification(s) for part features (where applicable)*
- ***Production quantity***

The first step in the library utilization exercise is to describe the various queries that would be made to the libraries. Each of these items is important as they can serve as key differentiators or constraints to reduce the number of candidate operations. However, a difficult task was to describe the part features and geometry.

Due to a lack of robust shape classification techniques, an approach better described as operation classification was initially developed. Table 1.4 shows the high level operation classification that was used for primarily material removal operations and also includes candidate operations associated with those operations. Table 1.3 clarifies the process codes used in Table 1.4. The description of operations was sufficient for exercising the example problem, but shape and/or operation classification appeared as a key barrier in achieving the ability to achieve more automation in process planning. The idea of progressing beyond operation into shape classification is a potential for future research. Note that the operation classification in Table 1.4 served as the preliminary basis for the feature taxonomy that was eventually developed and used in generating the process-feature mappings embedded in the version of the M-Library delivered to DARPA as a final deliverable.

Table 2.1: List of characteristics for typical components.

Material	Material Stock Form	Casting/Molding	Permanent Assembly	Wiring/Electrical Connections
2000 Series Aluminum (2014, 2024)	Flat Bar/Square Bar/Strip/Ingot	Permanent Mold Casting	Pressing (Interference Fit)	Zip Ties
5000 Series Aluminum (5052, 5053)	Round/Hexagon Bar	Sand Casting	Staking (Thread Inserts)	Conformal Coating
6000 Series Aluminum (6061, 6063)	Wire	Die Casting	Mig/Tig Welding	Labels
7000 Series Aluminum (7075, 7079)	Flat Plate and Panels	Investment Casting	Arc Welding	Staking Compounds
Cast Aluminum Alloy	Tooling Plate	Injection Molding	Spot Welding	Cable Overwrap
300 Series Stainless Steel	Sheet Metal	Sintering	Stud Welding	Molded Connector
400 Series Stainless Steel	Pipe/Tubing	Extruding	Laser Welding	Lubricants
Hi-Str. Stain. Steel (A-286, 17-4, 13-8)	Mechanical Tubing	Additive Manufacturing (STL, FDM,...)	Friction Welding	Light Oils
Cast Iron/Steel Alloy	Rolled Shape (angle, I-Beam,...)	Forming/Shaping	Brazing/Soldering	Heavy Oils
AISI 1000 Series Carbon Steel	Sphere	Hot/Cold Forging	Riveting	Dry Film Lubricants
AISI 4000 Series Steel (4130, 4340)	Billlet (molten)	Press Rolling	Crimping	Heavy Grease
AISI 8620 Carburizing Steel Alloy	Material Removal Operations	Bending (tube, bar, plate)	Adhesive Bonding	
HSLA Steel Alloy	CNC milling	Roll Bend Forming	Finishes	

Material	Material Stock Form	Casting/Molding	Permanent Assembly	Wiring/Electrical Connections
Armor Steel Alloy (RHA, HY-100,…)	Drill/Ream/Countersink	Wire Drawing	Primer	
100 Series Copper	Lathe turning	Spin Forming	Paint	
Brass/Bronze Cu Alloy	Thread Cutting/Forming	Shot Peening	Powder Coating	
Lead Alloy	Broaching	Embossing	Gold/Silver Plating	
Zinc Alloy	Plasma cutting	Sheet Stamping/Die Forming	Nickel Plating/Galvanizing	
Magnesium Alloy	Water Jet Cutting	Sheet Metal Deep Drawing	Acid Washing	
Plastic/Thermoset Polymer	Laser Cutting	Sheet Metal Bending	Iridite	
Elastomer	Sheet Metal Shearing	Heat Treatment	Annodize	
Phenolic	Sheet Metal Punching	Heat-Quench hardening	Passivation	
Fibreglass Composite	Electric Discharge Machining (EDM)	Annealing	Adhesives	
Carbon Fiber Composite	Chemical Etching	Normalizing	Alcohol Prep	
Glass/Ceramic	Saw/Abrasive Wheel Cutting	Tempering	Thread Locker	
Paper/Wood	Deburring Operations	Stress Relief	Silicone Sealants	
Textile	Precision Grinding	Surface Nitriding	VHB Tape	
Thermal Insulation	Hand Grinding	Surface Carburizing	Structural Adhesives	
	Sanding	Electron beam Surface Hardening		
	Bead Blasting			

Table 1.2: System level breakdown of a military ground vehicle.

System	SubSystem	Parts & Assemblies
Power Generation	Engine assembly	block, head, intake manifold, exhaust manifold…
	Engine cooling	radiator, coolant pump, drive belt, hose…
	Engine lubrication	oil reservoir, oil pump…
	Fuel system	tank, fuel pump, filter, level guage sender…
	Starter system	starter motor, alternator, voltage regulator…
Power Transmission	Transmission assy	case, gear, torque converter, clutch, bearing…
	Powertrain	drive shaft, u-joint, differential, axle, CV joint…
	Suspension	spring, shock absorber, control arm, ball joint…
	Steering	input shaft, pump, gearbox, rack & pinion…
	Wheel assy	wheel, tire, drive hub, lug, spindle, bearing…
	Braking	brake disc/drum, caliper, friction pad…
Chassis body	Base structure	frame, floor, roof, wheel well…
	Hull panels	fender, engine cover, cargo cover panel, doors...
	Armor panels	metal plates, composite panels, reactive armor…
Crew Cabin	Driver controls	steering column, throttle control, braking control…
	Seating	seat assembly, shock absorber elements, restraints…
	Electrical system	interior lighting, sensor control/display, wiper…
Auxiliary Systems	External lighting	headlight, marker light, spotlight…
	HVAC	compressor, clutch, condensor, evaporator, blower…

Table 1.3: Process code description.

Process Code	Process Type
DRP	Drill Press
WTJ	Abrasive Waterjet
WEM	Wire EDM
	CNC Milling
CNB	- bevel cut
CNE	- end mill
CNF	- fly cut
CND	- drill
CNU	- undercut
CNS	- spherical ball end mill
CNL	CNC Lathe
LSC	Laser Cutting
SHE	Shearing
BNS	Band Saw

Table 1.4: Operation classification for several machine types.

Feature Code	Feature Type	Can the process create the feature?													
		DRP	WTJ	WEM	CNB	CNE	CNF	CND	CNU	CNS	CNL	LSC	SHE	BNS	BND
	Through Features														
T-CYL	Cylinder	1	1	1	0	1	0	1	0	0	1	1	0	0	0
T-EXL	Exterior Linear Edge	0	1	1	0	1	0	0	0	0	0	1	1	1	0
T-INL	Interior Linear Edge	0	1	1	0	1	0	0	0	0	0	1	0	0	0
T-EXC	Exterior Complex Edge	0	1	1	0	1	0	0	0	0	0	1	0	0	0
T-SCR	Screw tap	1	0	0	0	0	0	1	0	0	0	0	0	0	0
T-INC	Interior Complex Edge	0	1	1	0	1	0	0	0	0	0	1	0	0	0
T-FIL	Fillet/Chamfer	0	1	1	1	1	0	0	0	0	0	1	0	0	0
	Blind Features														
B-CYL	Cylinder	1	0	0	0	1	0	1	0	1	0	0	0	0	0
B-SCR	Screw tap	1	0	0	0	0	0	1	0	0	0	0	0	0	0
B-CXP	Complex pocket	0	0	0	0	1	0	0	0	0	0	0	0	0	0
B-BEV	Bevel	0	0	0	1	0	0	0	0	0	0	0	0	0	0
B-REV	Revolute	0	0	0	0	0	0	0	0	0	1	0	0	0	0
B-SUR	Surface	0	0	0	0	0	0	0	0	1	0	0	0	0	0
	Deformation Features														
D-BND	Straight Bend	0	0	0	0	0	0	0	0	0	0	0	0	0	1

The next portion of the example involves the selection of test articles. Several articles were taken from the ULTRA-II blast bucket design performed by GTRI (see Fig. 1.5) and another example was used from Caterpillar information provided by the sponsor. The example from the ULTRA-II program was for a custom designed blast bucket for blast analysis. One of the panels used in this test article was evaluated and broken down into operations required for fabrication. The other example was selected from a Caterpillar product provided by the sponsor – a battery enclosure. These examples are described next.

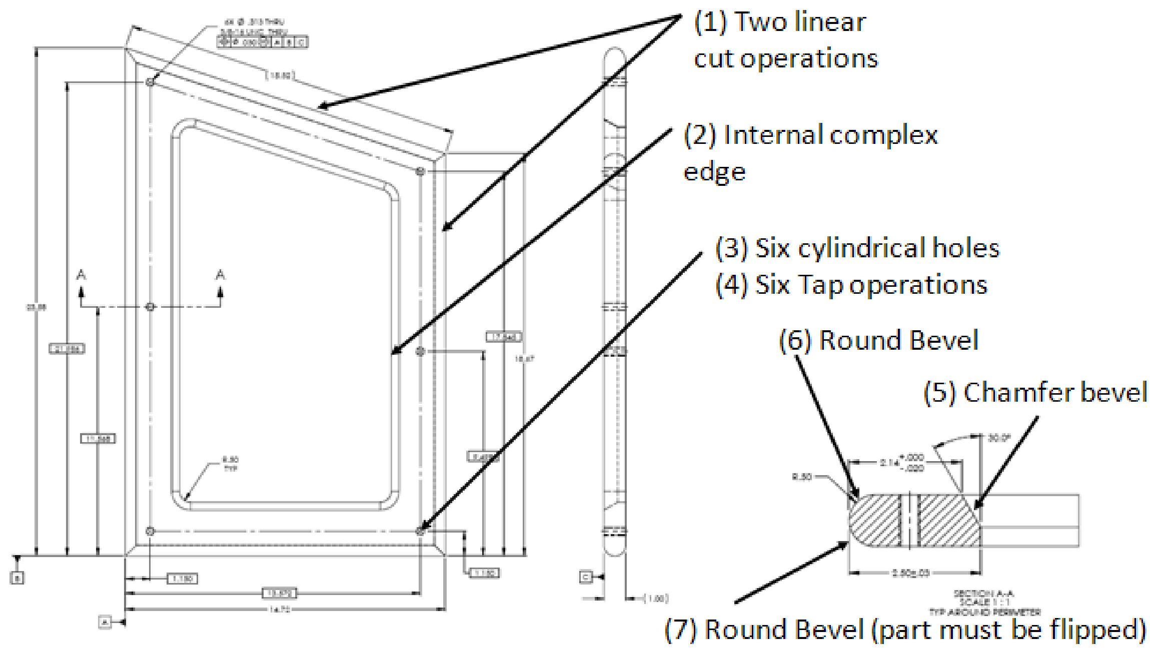


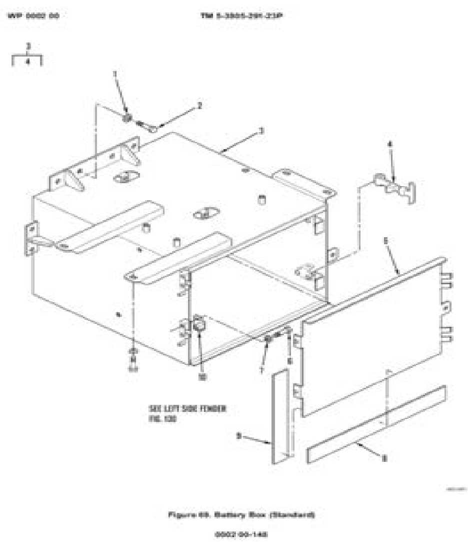
Figure 7.1: ULTRA-II example part - annotated with operations.

For the article depicted in Figure 1.1, a set of operations was selected to describe how the part could be fabricated. The operations are listed in Table 1.5. There are some important items listed in the aforementioned table. For one, the sequence is critical. If the sequence is not explicit and left to optimization routines, the computational complexity can increase exponentially. By stating a sequence, however, the process space has been reduced. In this particular example, various operations were grouped to consider benefits of doing some processes prior to others recognizing that the process planner was injecting bias into the process plan in doing so. Another key piece of information in Table 1.5 is the inclusion of a “feature normal.” It was decided that this type of information can be useful when the determination of the number of setups is considered for various processes. The last bit of information is feature surface area and feature volume removed. These parameters were considered beneficial for further evaluation such as cost analysis. For instance, a cost library could be built upon these parameters for a number of material removal operations.

Table 1.5: Sequence of operations for ULTRA-II example part.

Designer Input for ULTRA-90007							
	X	Y	t				
Bounding Box (in)	14.72	23.58	1				
-or-	X	r					
Bounding Cylinder							
Material	2	(RHA Plate)					
Feature Group	1	2	3	4	5	6	7
Feature Quantity	2	1	6	6	1	1	2
Feature Type	T-EXL	T-INC	T-CYL	B-SCR	B-BEV	B-BEV	B-BEV
Candidate Operations	WTJ	WTJ	DRP	DRP	CNB	CNB	CNB
	WEM	WEM	WTJ	CND	WEM		
	CNE	CNE	WEM				
	LSC	LSC	CNE				
	SHE		CND				
	BNS		LSC				
Feature Normal,X	0	0	0	0	0	0	0
Feature Normal,Y	0	0	0	0	0	0	0
Feature Normal,Z	1	1	1	1	1	1	-1
Tol, Location	1	1					
Tol, Size	0	1					
Feature Surf. Area (in2)	15.5	51					
Feature Vol Removed (in3)	36.1	155.2					

The next example is built upon a battery box from a Caterpillar vehicle. This box requires material removal, but also deformation as it is a folded sheet metal part. The assembly is depicted in Figure 1.2. Only the front panel was considered, but each of the sheet metal piece parts would be similar in regards to the composition of operations. The decomposition of operations is shown in Figure 1.3. The general format is the same with the exception of deformation operations – sheet metal bending. The general goal is that once a construct is in place for describing operations, the act of generating the decomposition for multiple parts becomes easier. The decomposition of operations is further described in Table 1.6. Remember that not only sequence, but orientation of the part, which is captured in the "feature normal" values can influence the results of automatic process planning routines.



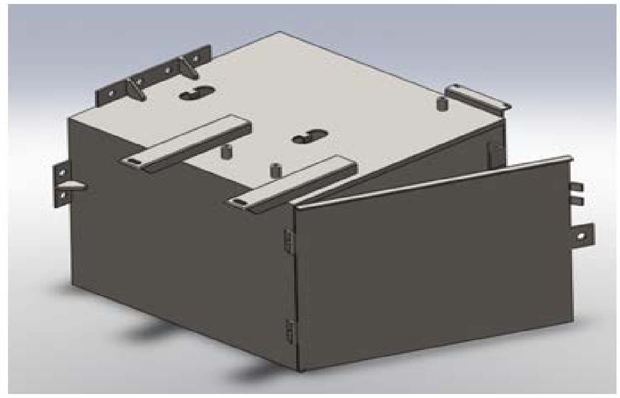


Figure 1.8: Caterpillar battery box model.

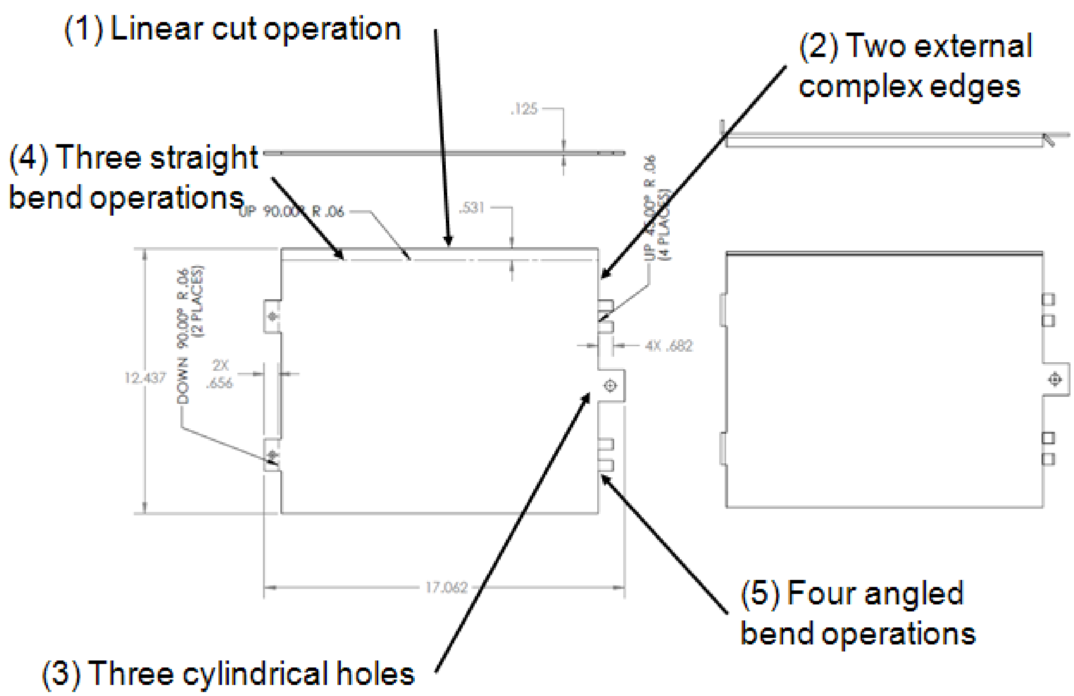


Figure 1.9: Operation decomposition of CAT battery box front cover.

Table 1.6: Decomposition of operations for CAT battery box front cover.

Designer Input for CAT Battery Box					
	X	Y	t		
Bounding Box (in)	17.062	12.437	0.125		
-or-	X	r			
Bounding Cylinder					
Material	2	Mild Steel			
Feature Group	1	2	3	4	5
Feature Quantity	1	2	3	7	4
Feature Type	T-EXL	T-EXC	T-CYL	D-BND	D-BND
Candidate Operations	WTJ	WTJ	DRP		
	WEM	WEM	WTJ		
	CNE	CNE	WEM		
	LSC	LSC	CNE		
	SHE		CND		
	BNS		LSC		
Feature Normal,X	0	0	0	0	0.71
Feature Normal,Y	0	0	0	0	0
Feature Normal,Z	1	1	1	1	0.71
Tol, Location	1	1	1	0	0
Tol, Size	0	1	2	0	0
Feature Surf. Area (in2)	15.5	51	0.89	0	0
Feature Vol Removed (in3)	36.1	155.2	0.34	0	0

One thing that is needed to support this example is not only a process library, but a capability library. When considering capability, one must have critical information captured for items present in the iFAB foundry. A generic foundry was created for exercising the example problems previously described. An example of this foundry is contained in Table 1.7.

Table 1.7: Representative example of foundry capabilities.

Machine No.	Description	Features	Location	Max Hardness	Requires Elec. Cond.?	Bounding Box			Bounding Cylinder		Thickness Limit (by material)		
						X	Y	t	X	r	1	2	3
5	Laser Cutting Bed	T-CYL	S-ATL	2	0	48	96	2			1	2	1.5
		T-EXL											
		T-INL											
		T-EXC											
		T-INC											
		T-FIL											
6	Sheet Metal Shear	T-EXL	S-ATL	1	0	48	96	1			0.8	0.5	0.25
7	Abrasive WaterJet Machine	T-CYL	N-ATL	2	0	52	27	4			4	3	2
		T-EXL											
		T-INL											
		T-EXC											
		T-INC											
		T-FIL											
8	Sheet Metal Brake	D-BND	N-ATL	1	0	48	96	0.25			0.25	0.13	0.06

The overall impact of the example problem exercises raised awareness of what was needed of the iFAB library. The importance of the need for shape classification, sequence of operations, and foundry parameter requirements was demonstrated in this example. Future work will need to consider the interactions and limitations or impacts associated with these findings.

Feature/Shape Classification

An example was described to address how operation or process classification was implemented as a means for the process planner to capture the designer inputs. A limitation was found in operation classification in that bias is easily injected into the process plan by assuming certain tools when using such a classification technique. A more generic approach of shape classification was considered to help address this limitation.

Although not complete, the current representation is that of a flow chart (see Figure 1.4). This approach goes through a selection process of shape profile, topology, and feature shape. Several limitations have been uncovered, which are listed below:

- **Degree of Difficulty –** Machine may be able to produce feature, but requires expensive / time consuming setup.
- **Special or Custom Tools –** Some features may require or benefit from a purpose-built cutter or tool.
- **Very Complex Features / Parts –** Gears, castings, and sprockets are examples of difficult to classify features.

The current work is well short of being complete and considerable effort will be required to generate a more comprehensive and robust classification system. Other considerations such as using a more standard format (SAT File) are still under consideration. An approach like this would require a means of grouping basic geometric shapes into features that are realizable on a manufacturing machine.

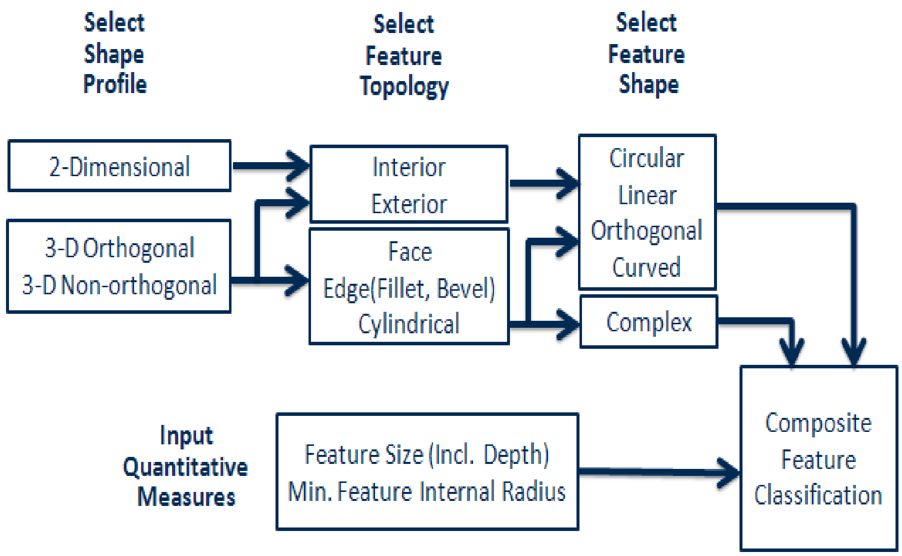


Figure 1.10: Flow chart describing initial shape classification approach.

ULTRA-II Test Case

The Georgia Tech Research Institute (GTRI), which is a part of Georgia Tech, has considerable experience with the fabrication of prototype military systems. One particular development was considered as a test case early in Georgia Tech's iFAB development – The ULTRA-II blast hull. Because this system was designed and fabricated by GTRI, the entire process was easily characterized and described to Georgia Tech's iFAB team for the purpose of a better understanding of the manufacturing process. Figure 1.5 has a detailed view of the structure with annotations of the major characteristics of the fabrication effort. Figure 1.6 contains a subassembly that was used during the fabrication effort. Additionally, a number of detailed drawings of piece parts were supplied to provide an initial test case for the GT iFAB development team. This information formed the basis for the library utilization example test cases discussed earlier. Table 1.8 details some of the parts and relevant materials associated with the Ultra-II that were considered in developing the library utilization examples.

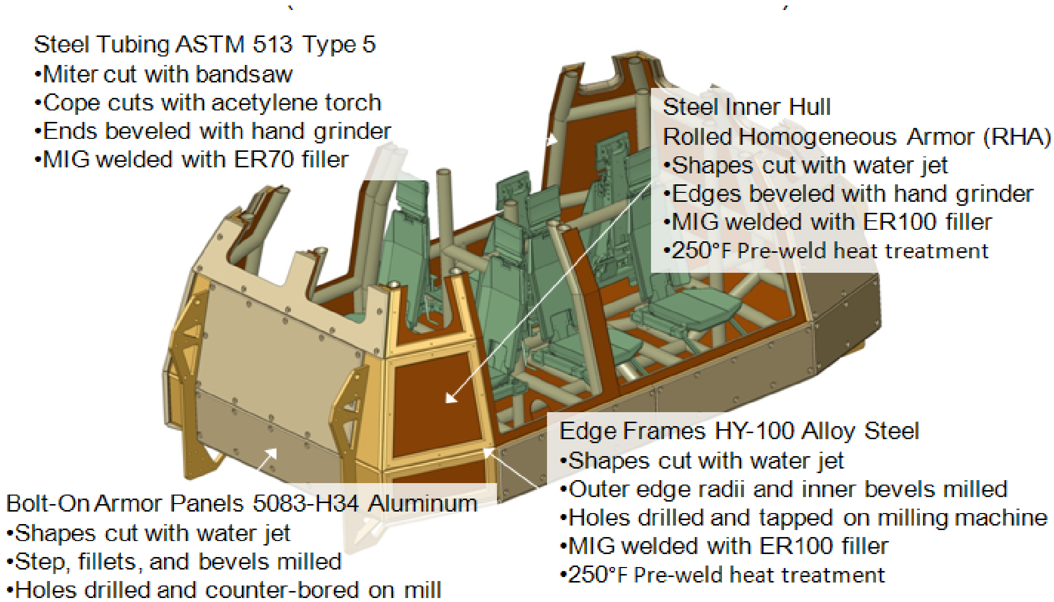


Figure 1.11: Isometric and annotated view of ULTRA-II hull.

Figure 1.12: Piece parts of ULTRA-II during fabrication.

Table 1.8: Several parts considered for ULTRA-II test case.

DRAWING	TITLE	DESCRIPTION	MATERIAL
ULTRA-90000	Tube Weldment	Bevel tube ends for weld preparation; align; weld process; filler material	1026 Steel Tubing ASTM 513 Type 5
ULTRA-90001	Tube 1	Planar cuts at angles through tube	1026 Steel Tubing ASTM 513 Type 5
ULTRA-90004	Tube 4	Cope cut at ends of tube	1026 Steel Tubing ASTM 513 Type 5
ULTRA-90005	RHA Plate	Cut plate outline (2D), 1/4" stock	RHA Steel Plate MIL-A-12560
ULTRA-90006	Quad Frame Plate	Cut plate outline (2D), 1" stock	HY-100 Alloy Steel
ULTRA-90007	Quad Frame Machining	Cut radius and bevel around perimeter; add threaded holes at dimensioned pattern	HY-100 Alloy Steel (Drawing says HSLA-100)
ULTRA-90008	Base Weldment	Bevel edges for weld preparation; align; preheat; weld RHA plate and edge frames to tube weldment; filler materials	1026 Steel Tubing RHA Steel Plate
ULTRA-90009	Upper Retainer	Round part with stepped, countersunk thru hole	Type 303 Stainless Steel
ULTRA-90010	Lower Retainer	Round part with thru hole (thin wall at one end)	Type 303 Stainless Steel
ULTRA-90011	B-Panel Machining	Cut plate ouline; angle cut and radius edges; create raised boss with beveled edges; thru holes with counterbores (near side and far side) at dimensioned pattern	5083-H34 Aluminum plate (Drawing says 6061 Aluminum)
ULTRA-90012	Fastener Installation	Insert parts in B-Panel and flare to retain; install flat head screw	Type 303 Stainless Steel retainers, alloy steel screw

4.2 Task 2: Manufacturing Knowledge Characterization (Primary Organization Responsible: Georgia Tech MaRC)

This task contains seven (7) sub-tasks, each of which deals with characterization (or modeling) of the capabilities of a specific class of manufacturing processes and associated machines and other pertinent resources. Initial effort in this task consisted of developing generic process and machine characterization templates and modeling guidelines that could then be used as the baseline upon which specific process and machine templates can be developed. An example of a early generic process model template is shown in Fig. 2.1. The figure also illustrates the color-coded systematic knowledge capture approach used to capture process/machine knowledge from the relevant domain knowledge experts on the GT iFAB performing team. Figure 2.2 shows the final process model template as implemented in M-SysML. Note that each manufacturing process concept (block) shown in Fig. 2.2 has its own detailed attributes, which can be exposed by expanding the concept within the MACME environment. Also, a specific manufacturing process (e.g. machining) inherits all attributes associated with the generic manufacturing process concept shown in Fig. 2.2.

Detailed attribute-based characterizations of specific manufacturing processes and machines were then carried out using knowledge capture exercises designed to adapt and expand the generic process (and machine) characterization template to include specific details of the different manufacturing processes and machines being modeled. Specifically, three rounds of manufacturing knowledge modeling exercises were performed by each sub-task performer to characterize various aspects of each manufacturing process, machines, and tooling. Sample results of these exercises are summarized in the following sections of the report. Due to the sheer number involved, detailed characterizations of every process, machine and resource modeled in the seven sub-tasks are not presented in the report. Instead, the emphasis is on presenting typical examples of the approach(es) used and key findings. The detailed characterizations of all processes/machines/resources are embedded in the MACME/M-Library software delivered to DARPA and posted on Sharepoint.

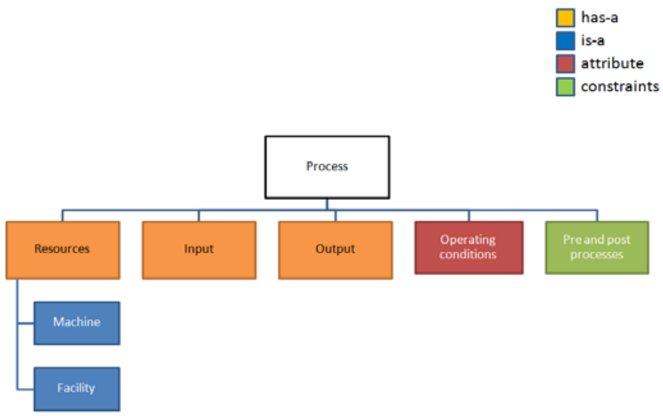


Figure 2.1: Generic template for a manufacturing process (version 1). The color code indicates the systematic modeling approach employed to acquire process and machine knowledge from the relevant domain knowledge experts.

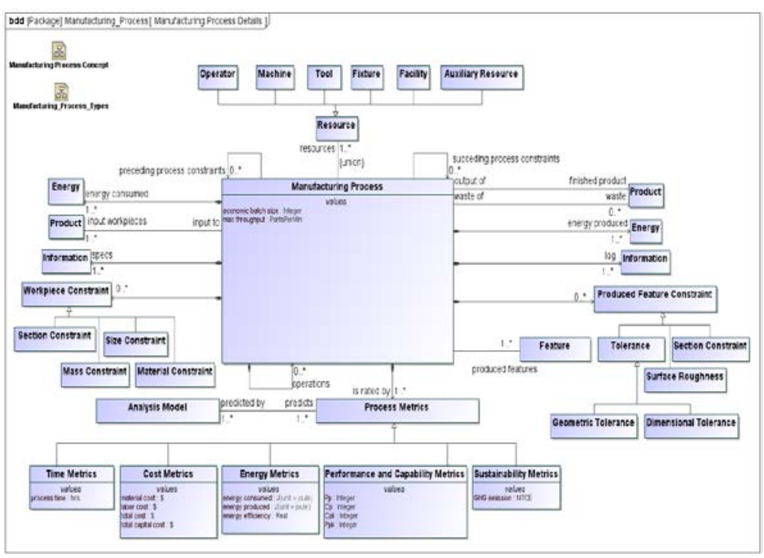


Figure 2.2: Final M-SysML definition of a generic manufacturing process (as implemented in MACME).

4.2.1 Task 2a: Characterize Conventional and Nontraditional Machining (Primary Organization Responsible: Georgia Tech MaRC, Lead: S. Melkote)

The main objective of this subtask was to characterize both conventional and non-conventional (or nontraditional) machining processes and associated resources such as machines, tools, etc. applicable for the manufacture of military ground vehicles.

Process Modeling

A taxonomical approach to process and machine characterization was employed. Figure 2a.1 shows the overall taxonomy of conventional machining processes modeled in this task. Some of the processes (e.g. milling) are further classified into sub-types (e.g. ball end milling, end milling, face milling, etc.).

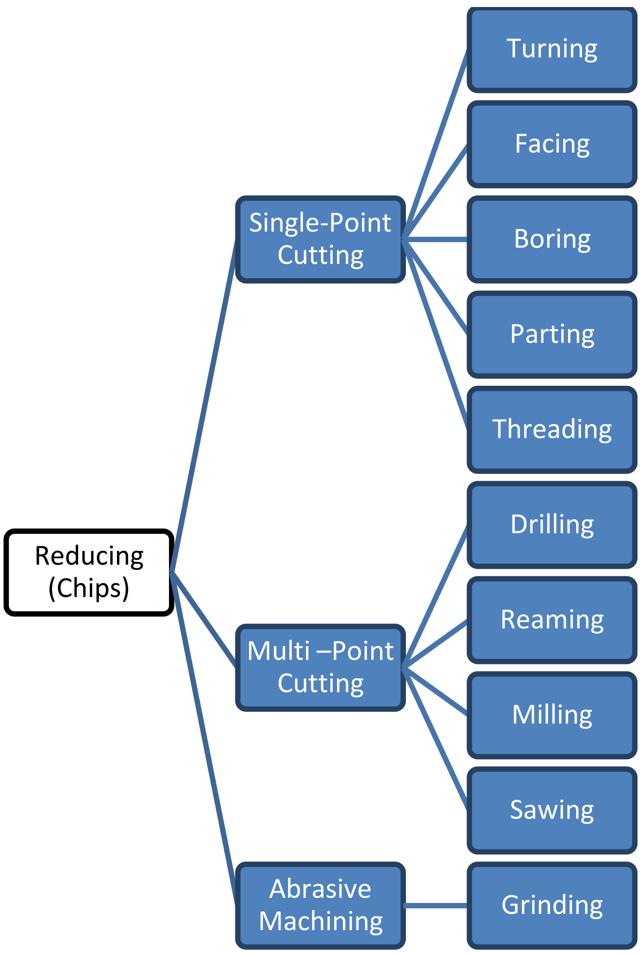


Figure 2a.1: Taxonomy of manufacturing processes: mass-reducing (data source: R. H. Todd and D. K. Allen, *Fundamental Principles of Manufacturing Processes*, Industrial Press Inc., 1994).

Table 2a.1 lists the conventional and nontraditional machining processes modeled in M-SysML and present in the M-Library. Each modeled process inherits all attributes associated with the definition of a generic manufacturing process shown in Fig. 2.2. In addition, a specific process can have specific attributes that owned solely by it.

Table 2a.1: Machining processes modeled.

Mechanical Removal Processes	Chemical, Electrical, Thermal Removal
Boring	Chemical Machining
Facing	Electrical Discharge Machining (EDM) Sinker EDM Wire EDM
Parting	Electron Beam Machining
Threading	Laser Cutting
Turning	Oxyfuel Gas Cutting
Drilling	Plasma Arc Cutting
Milling: Ball end milling Bevel cutting End milling Face milling Fly cutting	
Reaming	
Sawing	
Abrasive Water Jet Machining	
Ultrasonic Machining	
Blanking	
Shearing	

Process-Feature Mapping

Given a technical data package for a component, a key requirement for automated process selection based on geometrical attributes of the component is the need to embed a process-feature mapping for each process modeled in the M-Library. This in turn implies the need for a feature/shape classification system for all manufacturing processes that produce a feature (e.g. material removal processes, forming processes, etc.). Consequently, a part feature taxonomy that contains features producible by material removal processes was developed and is shown in Fig. 2a.2. Note that the features contained in this taxonomy are thought to be sufficient to describe the various geometric features commonly encountered in military ground vehicle parts that are machined.

At the highest level in the taxonomy, the defined features are independent of the manufacturing process. In its current implementation, text labels are used to define each feature in the taxonomy where each label implies a specific shape. Examples of shapes covered by each negative feature label are given in the Appendix (see Table A2a.1). Note that additional (quantitative) attributes and/or constraints based on size, material, etc. can be added to each feature definition to enable a more refined process selection.

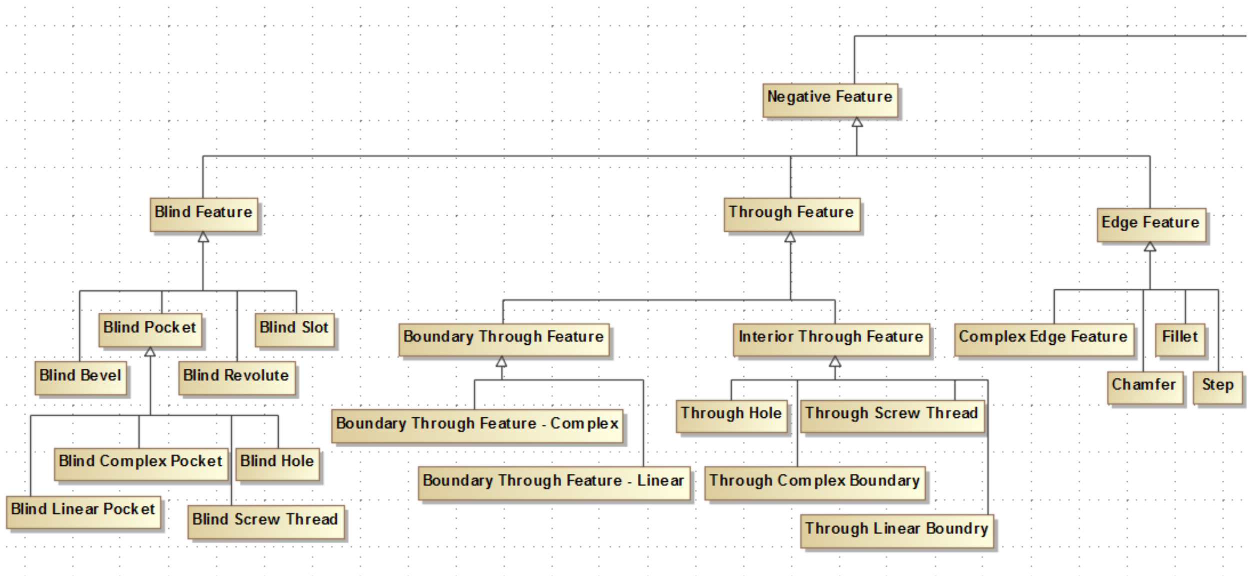


Figure 2a.2: Feature taxonomy for negative features.

Process-feature mappings for each machining process were generated from practical knowledge of its feature generation capabilities and modeled in M-SysML. This essentially involved associating each process with a list of (negative) features producible by the process. Once this mapping was implemented in the M-Library, queries about processes capable of producing features present in a CAD model of the component could be posed to the M-Library, which then returned a list of candidate processes available.

Note that, in its current state of implementation, the identification of specific features present in a CAD model of the component is a manual process. Future work can leverage the capabilities of automated feature recognition software or require the front end of the iFAB information architecture to manually (or automatically) annotate the CAD model of the component with the applicable feature labels.

Resource Modeling: Machines and Tools

Similar to process modeling, a taxonomical and attribute-based approach was adopted to characterize the capabilities of resources such as machines, tools, fixtures, operators, etc. associated with each machining process.

Figures 2a.3 and 2a.4 show sample characterizations of various machines used for conventional and nontraditional machining operations. Note that not all attributes (e.g. positioning resolution, repeatability, observed tolerance, etc.) are depicted in this figure but are contained in the M-Library implementation delivered to DARPA. Figure 2a.5 shows the machine taxonomy model for conventional machining as implemented in Magic Draw (SysML authoring tool).

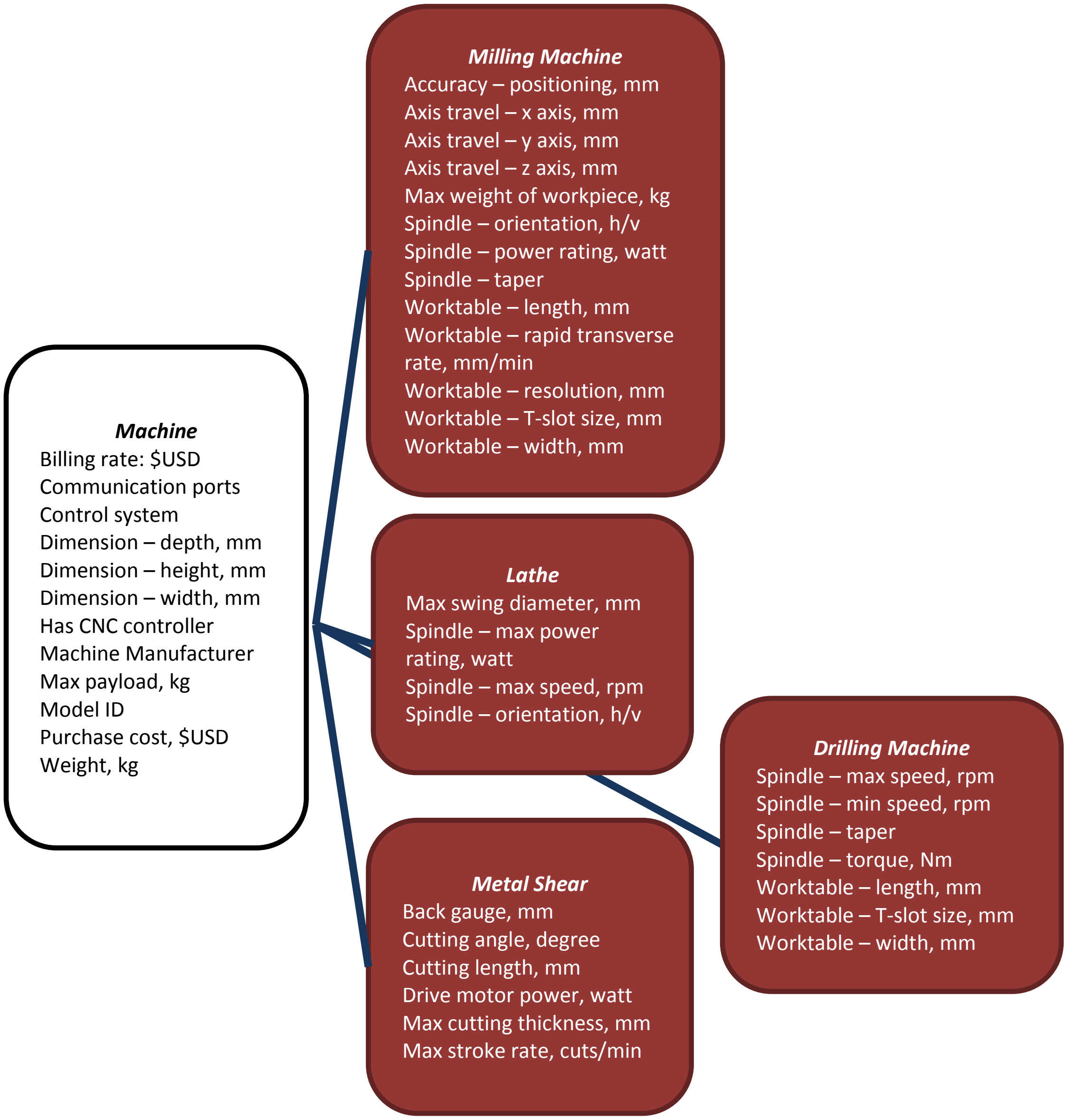


Figure 2a.3: Sample attribute-based definitions of machines used for conventional machining.

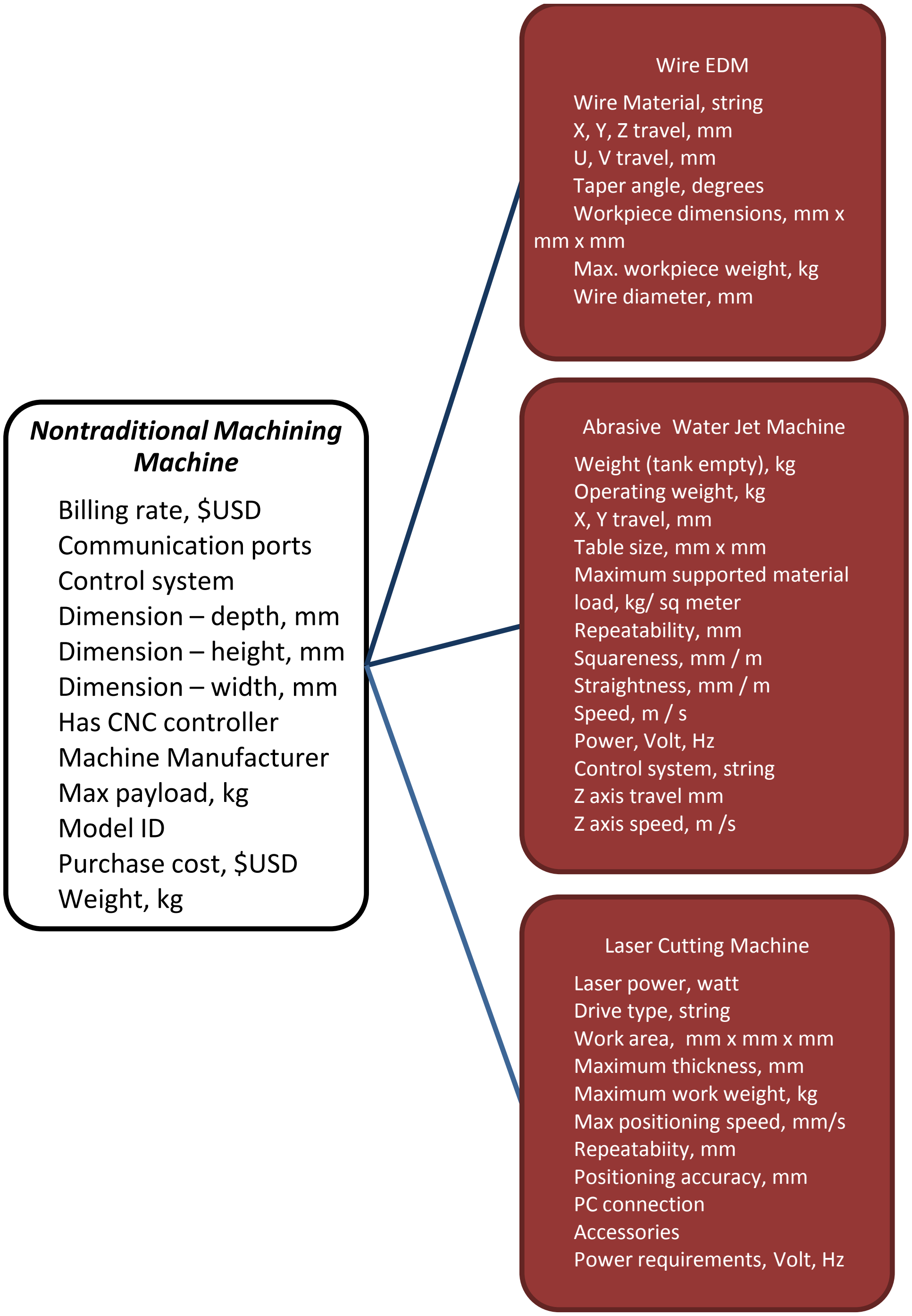


Figure 2a.4: Sample attribute-based definitions of machines used for nontraditional machining processes.

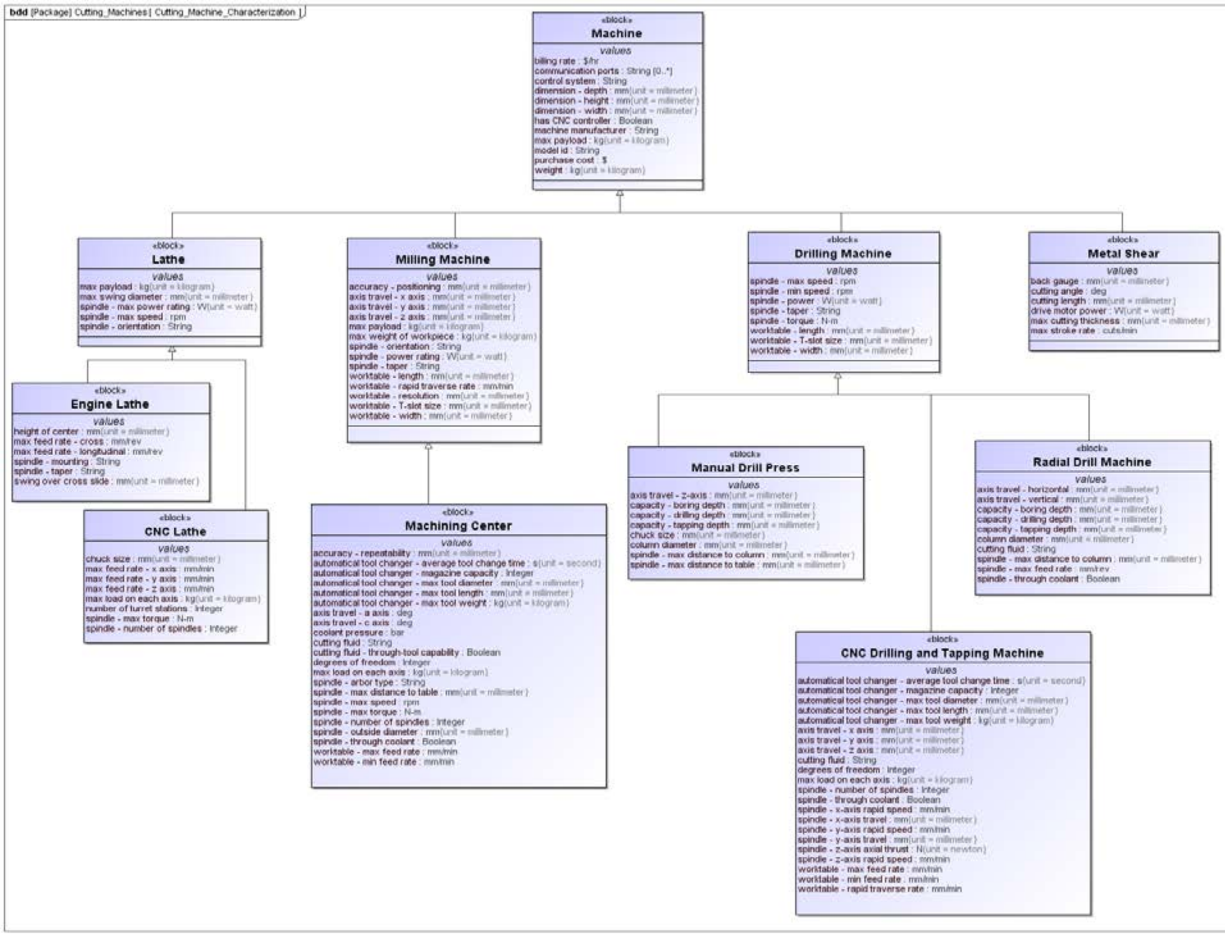


Figure 2a.5a: Machine taxonomy for conventional machining - SysML implementation.

Time and Cost Modeling

Machining time and cost models are needed to perform comparative performance analysis of candidate manufacturing processes/machines applicable for a given technical data package. To obtain desired economic operating conditions, the capability of processes and associated machines must be taken into consideration. Typical machine tool capability limitations include factors such as maximum permissible feed, speed, maximum power, maximum allowable cutting/thrust force, etc. Analytical models for computing time and cost for simple conventional machining operations such as milling, drilling and turning and for a few nontraditional machining processes such as wire EDM, abrasive water jet machining, and laser cutting were identified and are given in the Appendix (see Table A2a.2 and Equations A2a.1-A2a.26). Note that only the simplest time and cost models for a few of the conventional machining processes (e.g. milling, drilling) were implemented in the M-Library. The equations listed in the appendix cover additional cases not implemented in the delivered version of the M-Library.

Materials Considered

Machining time and cost analysis requires knowledge of machining conditions (feeds, speeds, depths of cut) for a given workpiece material. While it was beyond the scope of the present effort to develop a detailed materials database, a selected number of materials relevant to military ground vehicle parts was identified and recommended machining conditions for these materials were derived from a standard reference (Machining Data Handbook, Vols. 1 and 2, 3rd Edition, Institute of Advanced Manufacturing Sciences Inc.) and used in the sample time and cost calculations made for demonstrating the capabilities of the library. The list of materials considered is given in the appendix (see Table A2a.3).

Machine Instance Data

Instance data for several of the machine types were obtained from machine tool vendor websites and implemented in the M-Library. The final version of the MACME software delivered to DARPA has over 500 machine instances, including machines for conventional and non-traditional machining processes.

META-iFAB Assembly Exercises

The META-iFAB technical data package generated by the Vanderbilt META team for the January 2012 AVM PI meeting at Camp Pendleton was reviewed and specific fabrication parts were selected by the Task 2a team to develop a demonstration of the M-Library process and machine selection capabilities. Specifically, the chassis and some of the connecting parts shown in Fig. 2a.5 were chosen for demonstration.

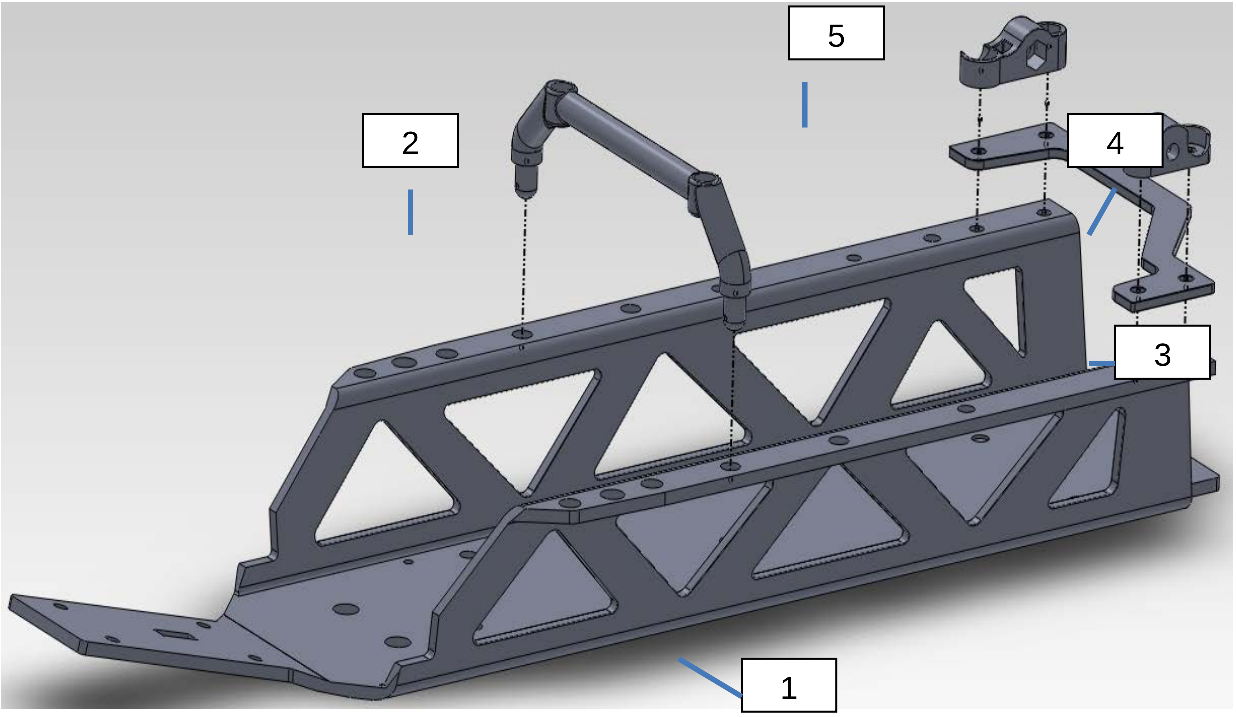


Figure 2a.5b: Exploded view of the first META-iFAB assembly exercise - chassis part.

The approach involved manually identifying features on the part to be fabricated, e.g. chassis shown in Fig. 2a.5b, and employing the process-feature mapping contained in the knowledge graph embedded in the M-Library to obtain responses to queries such as "What manufacturing processes can produce feature XX?". A flat plate was assumed to be the raw form of the starting material. Examples of part features identified for the are shown in Figure 2a.6. These feature names are derived from the feature classification system discussed earlier. Examples of the query results returned by the library are given in the Task 3 portion of this report.

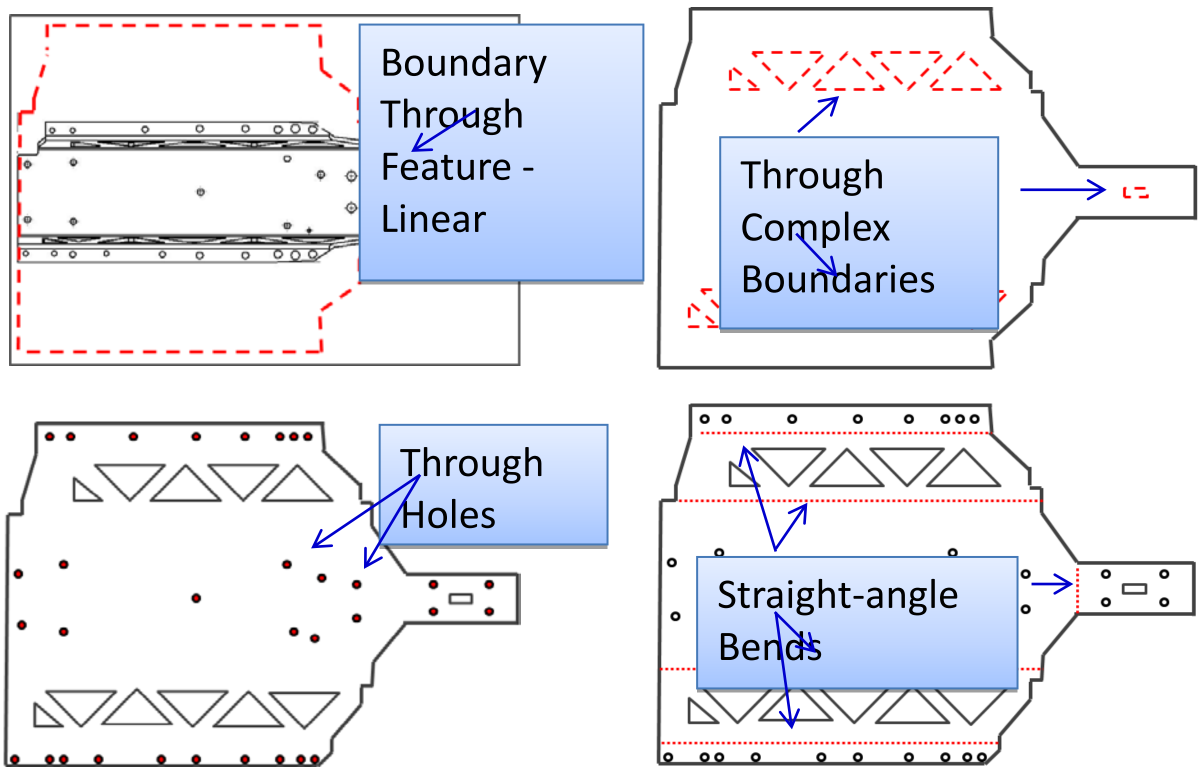


Figure 2a.6: Example features identified in the chassis part for process selection. Note that the starting material is assumed to be a flat plate.

Wrapper for Third Wave Systems Software

A software wrapper for batch mode execution of the physics-based Production Module machining simulation software from Third Wave Systems was developed and demonstrated at the May 2012 AVM PI meeting. The wrapper takes as input tool information from the M-Library (in the form of a .csv file), an NC toolpath file developed in any CAM software, and a STEP file containing the raw stock geometry and generates an input file for executing the Production Module software in batch mode. Due to current limitations of the Production Module code, true batch mode operation is not possible. Certain tool specifications (e.g. radial rake angle and number of flutes) must be entered manually into the appropriate menu inside the Production Module software following which the revised input file for simulation is created. The revised input file is then executed in batch mode by the wrapper to produce the simulation outputs from the Production Module (e.g. peak spindle power vs. time, peak resultant force vs. time, etc.). The wrapper also generates the charts from the simulation outputs. Figure 2a.7 shows a snapshot of the wrapper input screen while Figure 2a.8 shows the sample META part that was simulated for demonstration purposes.

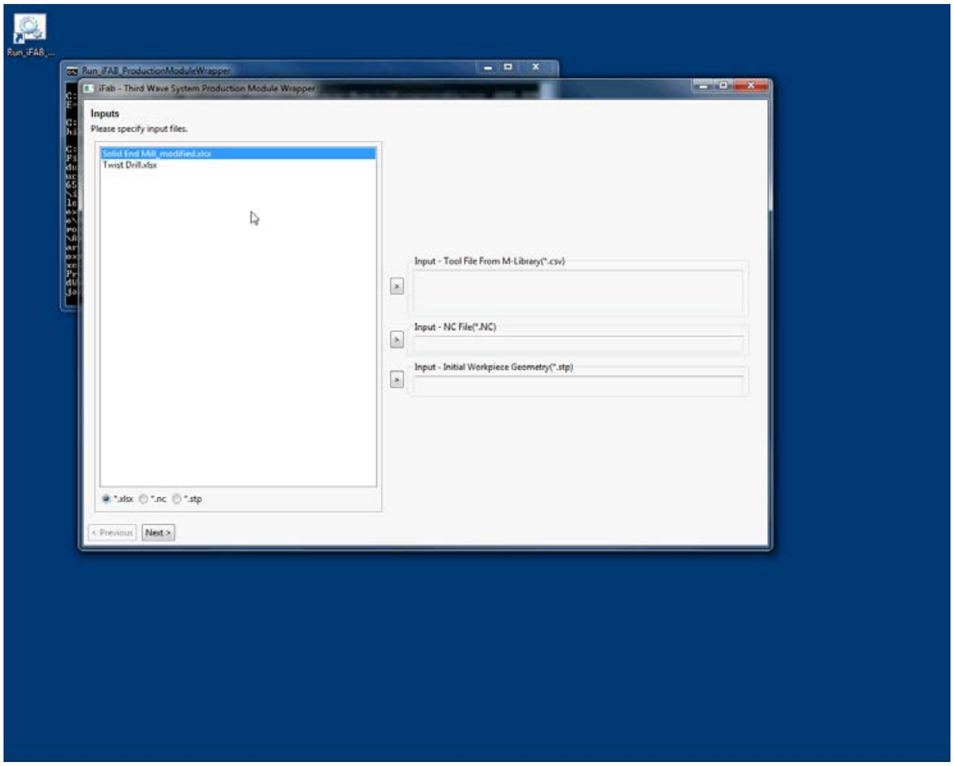


Figure 2a.7: Snapshot of Production Module wrapper input screen.

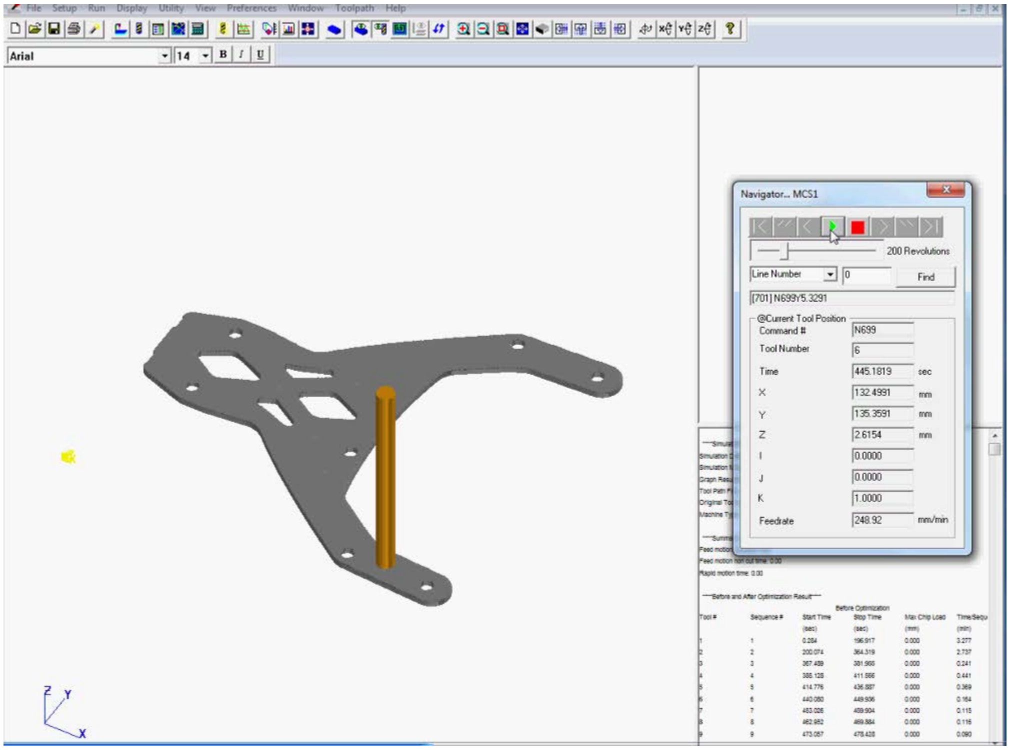


Figure 2a.8: Screenshot of Production Module demo part simulation using wrapper.

4.2.2 Task 2b: Characterize Forming Processes
(Primary Organization Responsible: Georgia Tech MaRC, Lead: S. Melkote)

The main objective of this task was to characterize metal forming processes and associated resources (e.g. machines) commonly used (or with the potential for use) in the manufacture of military ground vehicle parts. Metal forming processes can be categorized into bulk deformation and sheet metal forming processes. Examples of bulk deformation processes include rolling, extrusion, forging etc. while sheet metal processes include bending and stamping. Note that shearing and blanking processes, which are often grouped in the class of sheet metal forming processes, were modeled under machining processes since they involve material separation (by shear; see Table 2a.1).

Process Modeling

Table 2b.1 lists the forming processes that were characterized and modeled in the M-Library. The modeling approach used was similar to that adopted for modeling machining processes in that a taxonomy of different types of forming processes was created and selected forming processes (listed in the table) were modeled to varying degrees of completeness using a number of attributes for each process.

Table 2b.1a: Forming processes modeled.

Forming Processes
Bending
Radial bending
Roll bending
Straight-angle bending
Tube bending
Deep Drawing
Stamping
Drawing (rod/bar)
Extrusion
Forging
Hubbing
Piercing
Roll forging
Skew forging
Isothermal forging
Cogging
Orbital forging
Closed-die forging
Open-die forging
Edging
Fullering
Heading

Process-Feature Mapping

The process-feature mapping for forming processes followed the same feature taxonomy developed for machining processes. This was justified since most forming processes use dies, which are produced using machining processes.

Resource Modeling: Machines and Tools

Similar to the effort for modeling machining-related resources, machines for forming processes were also modeled. Table 2b.1b lists examples of the types of forging machines that were modeled.

Table 2b.1b: Forging machine classification.

Forming Process	*Machine*	
Forging	Hammers	Board hammer
		Air-life hammer
		Steam hammer
		Counterblow hammer
		Impacter
		Helve and trip hammer
	Forging Presses	Mechanical press
		Hydraulic press
		Screw press

The listed machines were characterized with several attributes. Tables 2b.2-2b.3 list the general and specific machine attributes for sample forging machines. Similar to machines for machining processes, all forming machines inherit the general attributes of the overarching machine definition.

Table 2b.2: General attributes of forging machines.

Hammer	***Forging Press***
• Rated size, kg • Ram stroke, mm • Ram front to back, mm • Blows per minuite, # • Blow energy, kJ	• Ram stroke, mm • Ram area, mm x mm • Table area, mm x mm • Blows per minuite, # • Drive motor, kW

Table 2b.3: Specific attributes of forging machines.

Board Hammer • Between the guides, mm • Sow block length, mm • Sow block thickness, mm • Diameter of rolls, mm • Center to center of belts, mm • Diameter and face of pulleys, mm	***Air-lift and Steam Hammer*** • Cylinder bore, mm • Inlet, mm • Exhaust, mm • Distance from top of anvil to bottom of guide, mm • Between guides, mm • Anvil cap front to back, mm • Closed die height, mm • Min die bearing area, mm x mm • Minimum striking area, mm x mm • Air consumption, mm^3 / min • Steam, kg / hour
Counterblow Hammer • Blow frequency at nominal working capacity, 1/min • Max ram stroke, mm • Max die height without dovetails, mm • Min die height without dovetails, mm • Daylight between guides, mm • Main motor capacity, kW	***Impacter*** • Rated force, N • Equivalent gravity hammer, kg • Equivalent power hammer, kg
Mechanical Press • Tonnage capacity, kN • Rated tonnage point, mm • Die height, mm • Slide adjustment, mm • Bolster thickness, mm • Slide opening, mm • Upper die weight capacity, kg	***Hydraulic Press*** • Press force, kN • Daylight between guides, mm • Ram speed, mm / s • Pressing speed, mm / s
Screw Press • Max permissible force, tons • Screw diameter, mm • Distance between table and ram-up, mm • Distance between table and ram-down, mm	

4.2.3 Task 2c: Polymer and Composites Processing
(Primary Organization Responsible: Georgia Tech MSE, Lead: D. Yao)

The main objective of this subtask was to characterize the major polymer/composites manufacturing processes used for manufacturing military ground vehicles. The primary polymer/composites manufacturing processes for military ground vehicles were identified and the required taxonomy for classifying different processes was developed. Focused studies were conducted to understand the unique attributes of each process and the resources involved. Particular efforts were made to characterize the ten most important processes (resin transfer molding, resin infusion molding, prepreg lay-up, wet lay-up, injection molding, SMC compression molding, structural reactive injection molding, spray-up, thermoplastic injection molding, thermoforming and GMT compression molding) using an object-orientated process characterization framework. Under this framework, process models were established for each process, especially for resin transfer molding and injection molding.

Process Modeling

Polymer/composites manufacturing processes for military ground vehicles can be divided into two main groups: thermosetting processes and thermoplastic processes, as shown in Figure 2c.1. Thermosetting processes dominate in composites manufacturing, accounting for more than 70% processing activities and are extensively used for manufacturing high performance continuous fiber reinforced polymer composites.

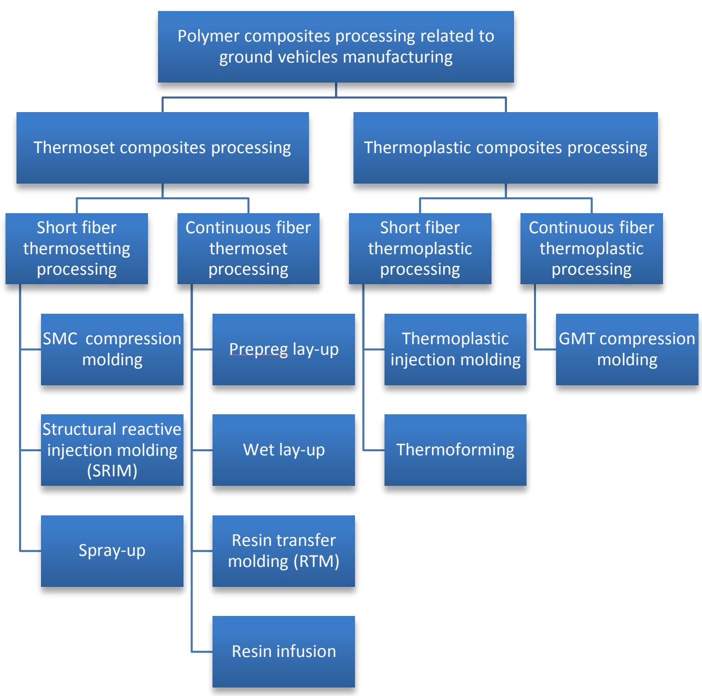


Figure 2c.1: Polymer/composites processing methods for military ground vehicles.

The primary attributes of a polymer/composites manufacturing process are shown in Figure 2c.2. Material, shape and size are among the most basic attributes. It is indicated from the diagram that each attribute has to include more details for describing this specific process. For example, the material attribute depicts a collection of resin system and reinforcement fibers for all processes, but must be specified for a specific process. The framework, therefore, represents a general description for all polymer/composites manufacturing processes, which will have specialized value for each process. In the following sections, the structure and scope of each important attribute of a polymer/composites manufacturing process are described in more details. Together, these attributes spell out the unique process characteristics of a polymer/composites process including distinctive processing capabilities.

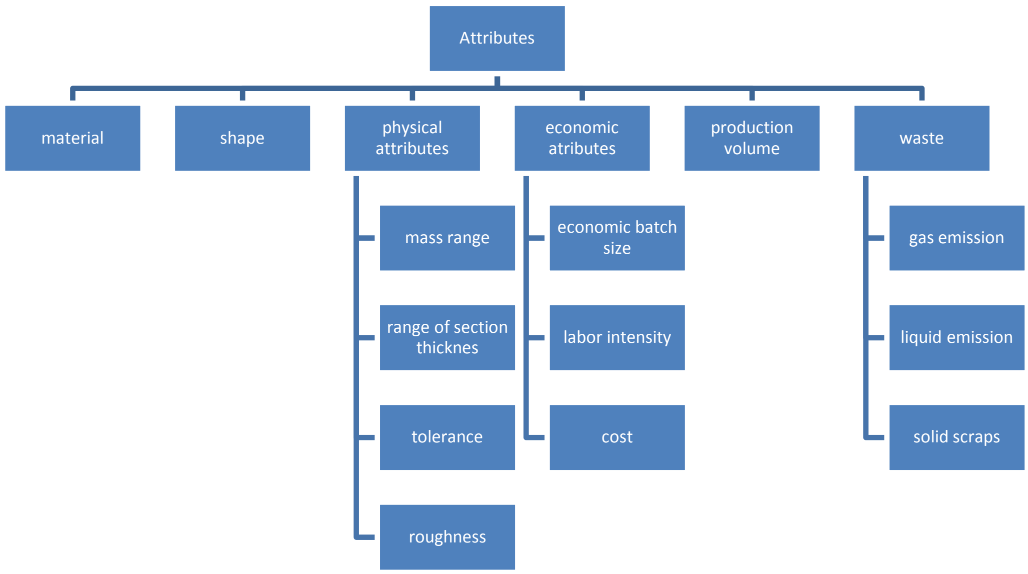


Figure 2c.2: **Primary attributes of a polymer/composites manufacturing process.**

Material: The structure of the material attribute of a polymer/composites manufacturing process is specified in Figure 2c.3.

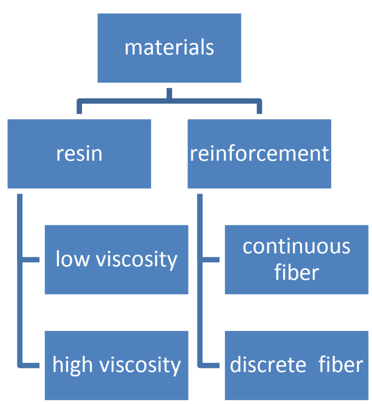


Figure 2c.3: The structure of the material attribute of a polymer/composites process.

Shape: A key attribute of a process is the family of shapes that the process can produce. Basic shapes may be classified according to the processes that form the shapes. For example, prismatic shapes and sheet shapes are produced by different processes. This method is currently used in a commercial materials and process selection software called CES EduPack™. The most basic shapes according to this classification method are shown in Figure 2c.4.

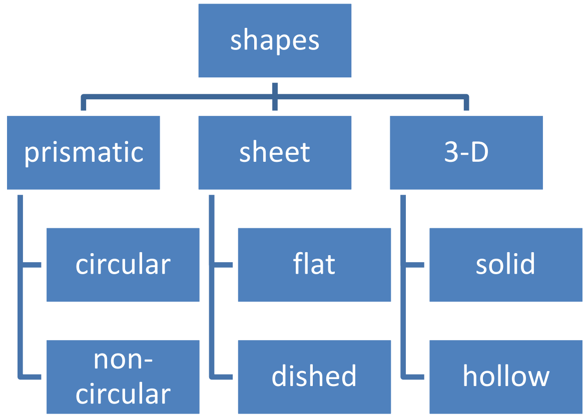


Figure 2c.4: The structure of the shape attribute of a polymer/composites process.

Mass range and section thickness: There are limits to both the size (simplified by the mass measured) and the section thickness (the thickness of the finished shape) that a process can handle. Sometimes the limits are purely practical: a more extreme size or thinner section can be made, but – because of the cost of time and equipment involved – it is not normally economic to do so. However, there are fundamental limits, too. Molding relies on material flow in the liquid or semi-liquid state. Lower limits on section thickness are imposed by the physics of flow. Upper limits to size and section in molding are set by problems of shrinkage.

Tolerance and roughness: No process can shape a part exactly to a specified dimension. Some deviation from a desired dimension is permitted; it is referred to as the *tolerance T*. Closely related to this is the *surface roughness R*, measured by the root-mean-square amplitude of the irregularities on the surface. Manufacturing processes vary in the levels of tolerance and roughness they can achieve economically. Molded polymers inherit the finish of the molds and thus can be very smooth, but tolerances better than ±0.2 mm are difficult because internal stresses left by molding cause distortion and because polymers creep in service. Moreover, processing costs increase almost exponentially as the requirements for tolerance and roughness are made more severe.

Economic batch size: Generally, the economic batch size is the number of units that must be manufactured for the process to be economic, meaning that it is cheaper than competing processes.

Labor intensity: Labor intensity stands for automatic level of the process, and it is also a significant part of cost. Ranking of labor intensity (hours per unit) of process enables comparison of different processes. It is categorized qualitatively on the discrete scale from 'very high' – 'low'.

Mappings between Processes and Process Inputs

Mappings between polymer/composites manufacturing processes and various process inputs including part features, geometrical shapes, and types of materials have been established.

Mapping between processes and part features: This mapping was developed to assist in programming with a manufacturing domain-specific modeling language. With this mapping, a suitable process from the manufacturing processes database for fabricating the specific part feature can be determined. The types of features that can be manufactured by polymer/composites processes were identified, as shown in Figure 2c.5. Simultaneously, it is necessary to identify the features that can be produced by each process. The benefit of mapping features with each process is to locate the best suitable manufacturing process in combination with time and cost models. The features produced by each process are given in Table 2c.1.

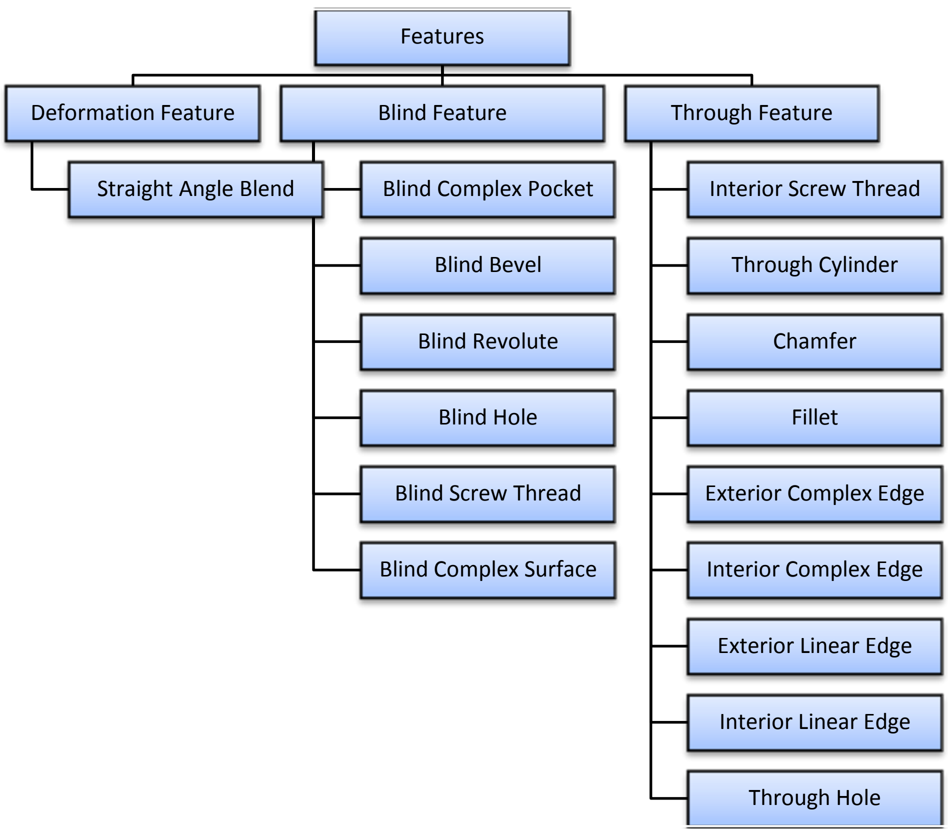


Figure 2c.5: Features produced by polymer/composites manufacturing processes.

Table 2c.1: The features produced by each polymer/composites manufacturing process.

Process name	Types of features															
	Deformation features	Blind features						Through features								
	Straight angle bend	Blind complex pocket	Blind bevel	Blind revolute	Blind hole	Blind screw thread	Blind complex surface	Interior screw thread	Through cylinder	Chamfer	Fillet	Exterior complex edge	Interior linear edge	Through hole	Interior complex edge	Exterior linear edge
SMC Compression Molding	X	X	X	X	X		X			X	X	X				X
SRIM	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Spray-up	X	X	X	X	X		X			X	X	X	X	X	X	X
Prepreg lay-up	X	X	X	X	X		X			X	X	X	X	X	X	X
Wet lay-up	X	X	X	X	X		X			X	X	X	X	X	X	X
Resin Transfer molding	X	X														
Injection molding	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Thermoforming	X	X	X	X	X		X			X	X					
GMT compression molding	X	X		X	X		X			X	X	X				X
Resin infusion	X	X	X	X	X		X			X	X	X				X

Mapping between processes and input shapes: The purpose of this mapping was to identify the range of part shapes that each process can deal with. This mapping is also helpful in selecting the best suitable process for fabricating a special part. To make this mapping more precise, a survey of shape classifications and selected Schey's classification system (shown in Figure 2c.6) was conducted to identify typical shapes in ground vehicle parts. Likewise, the types of shapes that can be input to each process for the processes in the polymer/composites manufacturing domain were identified. The detailed coding system is given in Table 2c.2.

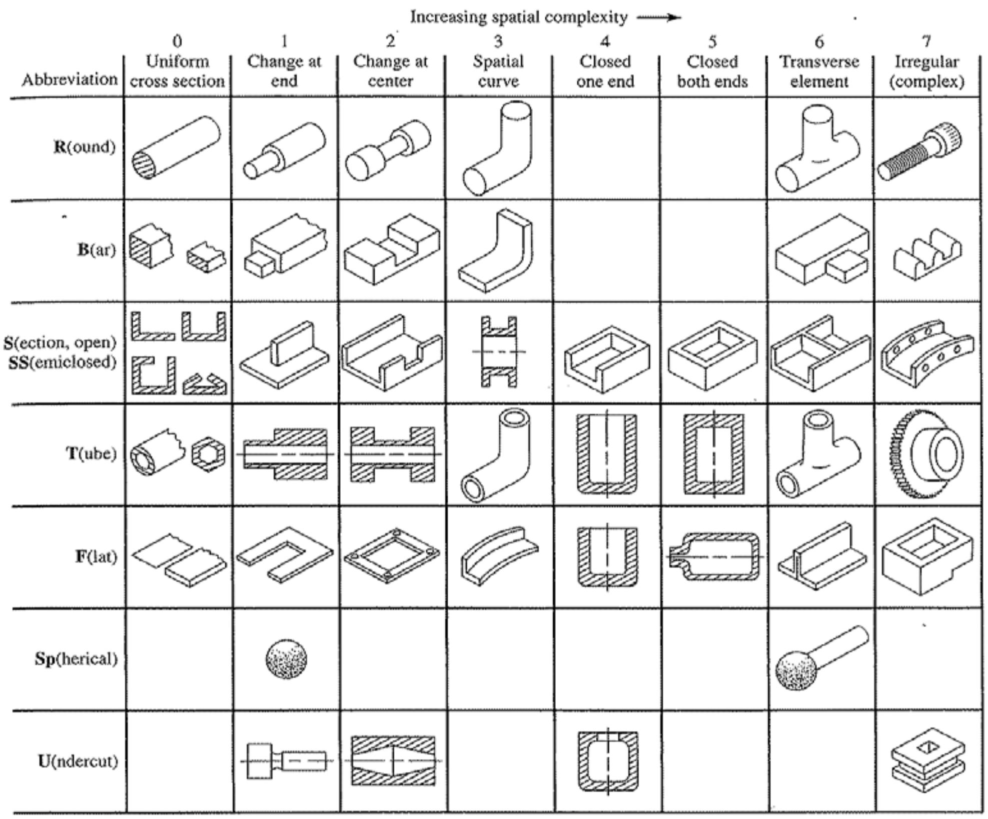


Figure 2c.6: Schey's shape classification system.

Table 2c.2: Shapes that can be dealt with by each polymer/composites manufacturing process.

Process Name	Shape Codes
SMC Compression Molding	B0-B3,B6-B7;S0,S2,S6;T4;F0-4,F6
SRIM	R0-R3,R6-R7;B0-B3,B6-B7;T0-T7;F4;SP1,Sp6;U1,U7
Spray-up	B3;S0,S4,S5;T4,T5;F0-1,F3-4,F7
Prepreg lay-up	B3;S0,S4,S5;T4,T5;F0-1,F3-4,F7
Wet lay-up	B3;S0,S4,S5;T4,T5;F0-1,F3-4,F7
Resin Transfer molding	R0-R3,R6-R7;B0-B3,B6-B7;S0-S7;T0-T7;SP1,Sp6;U1,U7
injection molding	R0-R3,R6,B0-B3,B6,B7,S0-S7,T0-T4,T6-T7,F0-F4,F6,F7,Sp1,Sp6,U1,U7
thermoforming	B3,S0,S4,S5,T4,F3,F4
GMT compression molding	B2,B3,B7;S0,S2-S7;T4;
Resin infusion	B0-B3;S0-S3,S4-S7;T4-T5;F0-F4;F6-F7;

Mapping between processes and materials: The types and forms of materials that can be utilized for all polymer/composites manufacturing processes are summarized in Figure 2c.7. For all ten polymer/composites manufacturing processes, a list of materials commonly used in ground vehicle applications was compiled. A range of material property values, including density, strength, and temperature for the material grades applicable for polymer/composites manufacturing were collected.

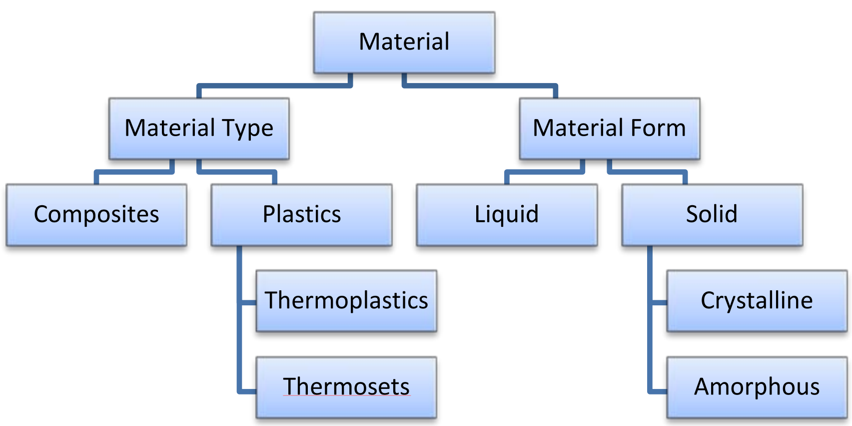


Figure 2c.7: Material types and forms for polymer/composites manufacturing.

Time and Cost Models for Unit Polymer/Composites Processes

Simple time and cost models for polymer/composites manufacturing processes were developed. Approximate estimates of the time and cost of producing a polymer/composite part can be made from these models. In these models, the intrinsic parameters including fixed parameters for the machine (e.g. cost per hour), fixed parameters for the machine tool, geometric parameters for the feature, and material properties of the component (e.g. cost per pound) were used. A general expression for time of manufacturing a part was derived, as shown in Equation (2c.1).

$$T = T_s + T_f + T_p \quad \text{(Eqn. 2c.1)}$$

Where T_s is setup time of a part, T_f represents fabricating time of a part, and T_p is the post-processing time of a part. For a specific process, T_f can be obtained from an appropriate physics model involving the processing parameters and material parameters. The post-processing process may include inspecting, trimming, cleaning, or moving the parts. It starts from the moment when the material is placed into the mold and ends when the part is moved out of the mold. The total cost of one part can be calculated using Equation (2c.2).

$$C = C_m + C_s + C_p + C_t + C_a + C_f \quad \text{(Eqn. 2c.2)}$$

where C is the total cost of a part, C_m is the material cost of a part, C_s is the setup cost of a part, C_p is the post-processing cost of a part, C_t is the tooling cost of a part, C_a is the cost of auxiliary resources, and C_f is the fabrication cost which mainly includes machine cost and labor cost in processing. The cost of auxiliary resources may include cost of mechanical cutters, laser cutters, autoclaves and ovens. The actual involvement of resources varies with processes. The fabrication cost is process specific and needs to be calculated in terms of the particular setup of a process. Time and cost models for a unit-level process can provide an estimate of time and cost needed for manufacturing a part, which plays an important role in selecting the best suitable process. If two processes can fabricate the same part, the process with less time and cost will be selected.

Illustration of time and cost calculation for injection molding was described in the 6MAC report. In this report, a refined cost model for resin transfer molding is presented.

Resin Transfer Molding

The total cost per piece for a resin transfer molded part mainly includes material cost, production cost and mold cost. The cost model can be expressed by the following equation:

$$C_{total} = C_{material} + C_{a-material} + \frac{C_{mold}}{N} + C_1(T_{setup} + T_{heating}) + C_2(T_{injecting} + T_{curing}) + C_3 T_{post}. \quad \text{(Eqn. 2c.3)}$$

The definitions of the parameters involved in this equation are given in Table 2c.3.

Table 2c.3: Definitions of parameters in the cost model for resin transfer molding.

Symbol	Definition	Unit
C_{total}	Total cost per part	$
$C_{material}$	Thermosetting resin cost per part	$
$C_{a\text{-}material}$	Auxiliary material cost per part, including catalyst, release agent and gel coat	$
C_{mold}	Cost of mold	$
N	Number of times (cycles) the mold can be used	
C_1	Unit time cost for setup	$/hr
T_{setup}	Setup time before processing	hr
$T_{heating}$	Time for the mold to be preheated after clamped	hr
C_2	Unit time cost for processing	$/hr
$T_{injecting}$	Injecting time	hr
T_{curing}	Curing time	hr
C_3	Unit time cost for post processing	$/hr
T_{post}	Post processing time	hr

A detailed example of time and cost calculations for injection molding was presented in the 6MAC report already submitted to DARPA and is therefore not reproduced here.

4.2.4 Task 2d: Characterize Additive Manufacturing Processes and Machines (Primary Organization Responsible: Georgia Tech MaRC, Lead: D. Rosen)

The objectives of this sub-task were to:

1. Develop a taxonomy of additive manufacturing (AM) processes and related concepts.
2. Develop first order models for predicting time and cost of unit manufacturing processes.
3. Characterize manufacturing processes and related concepts in-depth.
4. Implementation of build time and cost models – AM Select.
5. Develop AM material taxonomy.
6. Develop AM specific feature taxonomy.
7. Build material database according to (4).
8. Build actual parts and measure build time to verify (2).

Process Modeling

The AM taxonomy includes process, machine, and auxiliary equipment taxonomies. Corresponding definitions are also presented in tabular form. Figure 2d.1 shows an example of the process taxonomy.

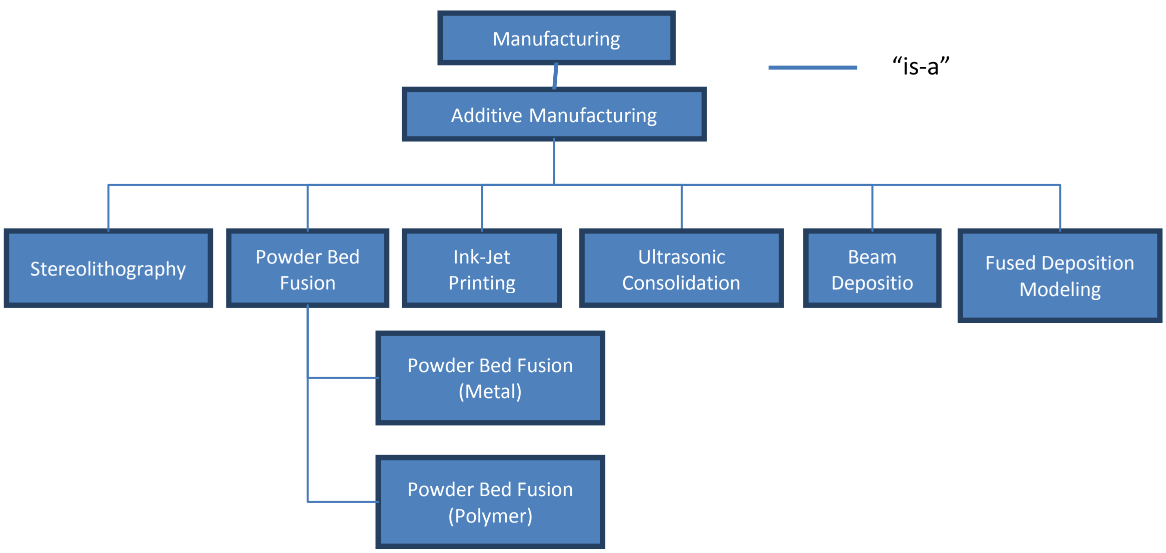


Figure 2d.1: AM process taxonomy.

In Fig. 2d.1, the taxonomy identifies various AM processes including Stereolithography, Powder Bed Fusion, Ink-Jet printing, etc. with their hierarchical relationships. This process taxonomy serves as a foundation for developing more specific taxonomies, such as AM machine and auxiliary equipment taxonomies.

Time and Cost Modeling

Build time and cost models were developed and implemented separate from the M-Library. The algorithms for time and cost calculations utilize machine specific attributes such as build volume, laser scanning speed, material deposition rate, and machine cost to compute build time and cost estimate. The details of the algorithm are included in the appendix.

Finally, AM machines for each process in Fig. 2d.1 are characterized by identifying important attributes that distinguish each machine and support build time and cost estimation. Categories of attributes include build qualities, build volumes, and machine component dimensions and speeds (e.g., laser beam size and scanning speed). These machines have been instantiated in the M-Library.

To demonstrate the usefulness of the taxonomies, algorithms, and machine characterizations, an AM selection tool, called AM-Select, that supports design activities was developed. In this tool, the taxonomies, algorithms, and machine specifications were encoded in software and feasible AM machines were identified for a given design specification and further estimates build time and costs. The following paragraphs discuss an example of AM-Select utilization.

First, a part to be manufactured is discussed in terms of its design specifications. Then, a web-based AM Selection tool utilization is described. Finally, implications of AM-Select in supporting design tasks are discussed.

In Fig. 2d.2, a part to be manufactured is shown. For this example, the part material can be any metal and the side wall is smooth (surface finish < 0.1 Ra).

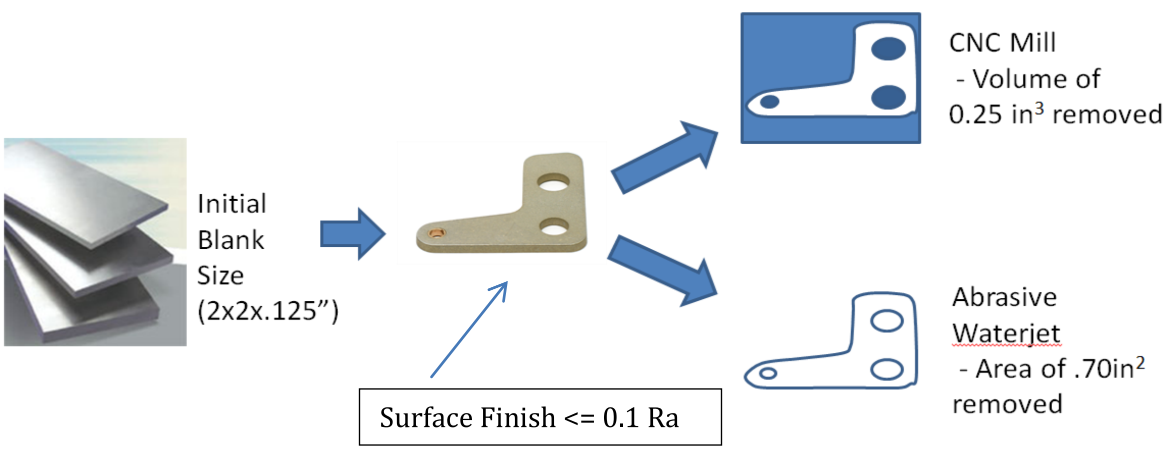


Figure 2d.2. Part and its design specification.

The design specification is then submitted to AM-Select as shown in Fig. 2d.3. AM-Select only requests design specifications that are utilized to identify feasible machines and compute build time and cost estimates.

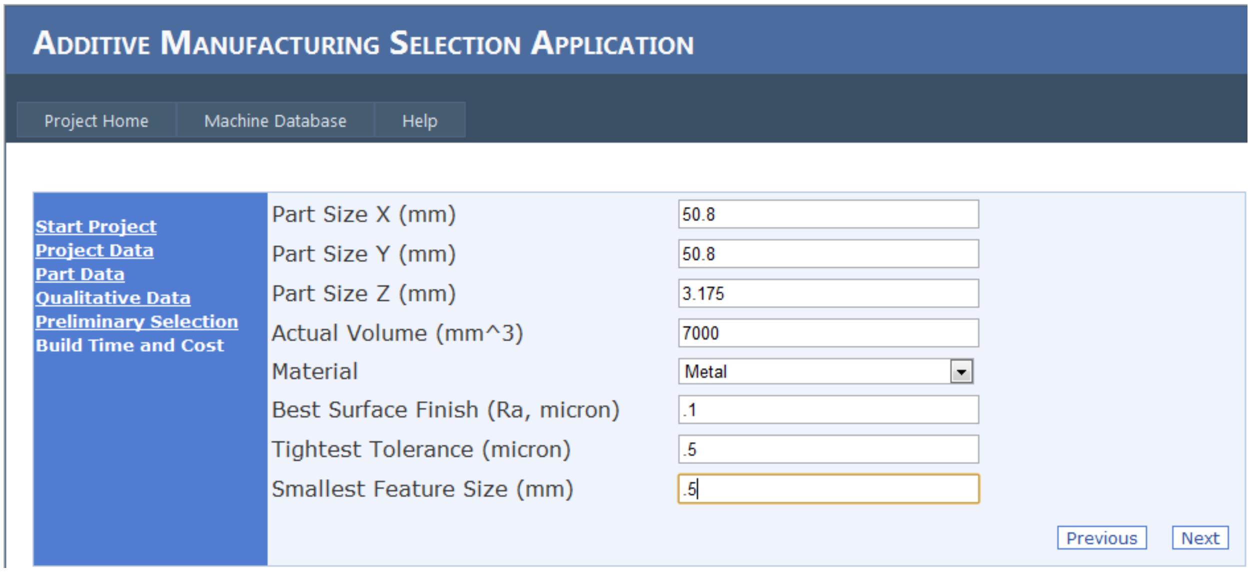


Figure 2d.3 Input of design specification.

Based on the specification, AM-Select identifies recommended and not recommended machines as shown in Fig. 2d.4. This identification is performed by finding machines that can satisfy the design specifications. Hence, design specifications and machine characterizations are compared to find a list of recommended machines.

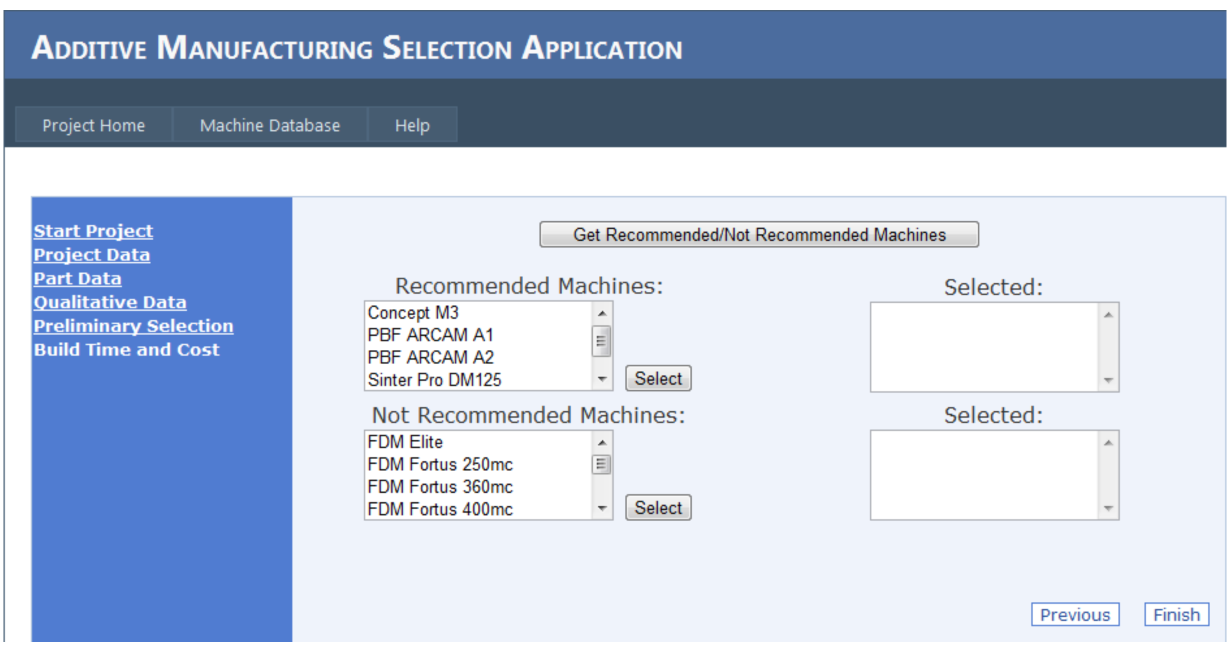
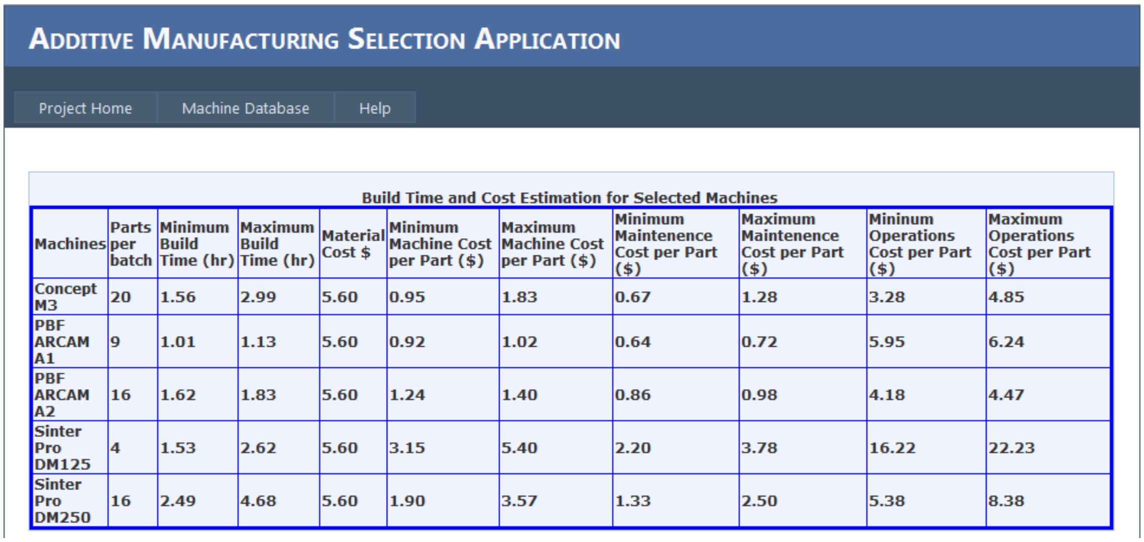


Figure 2d.4 Candidate machines.

After selecting machines from the recommended machines list, AM-Select computes the build time and cost estimates for each machine using the implemented algorithm and design specification. As shown in Figure 2d.5, detailed cost estimates including material, machine, maintenance, and operational costs are displayed. Furthermore, the number of parts that can be built at once and corresponding build time is shown. Based on the preliminary result in Fig. 2d.5, the designer can further refine design specifications or select one or more of the available technologies to build the part.



Build Time and Cost Estimation for Selected Machines

Machines	Parts per batch	Minimum Build Time (hr)	Maximum Build Time (hr)	Material Cost $	Minimum Machine Cost per Part ($)	Maximum Machine Cost per Part ($)	Minimum Maintenence Cost per Part ($)	Maximum Maintenence Cost per Part ($)	Mininum Operations Cost per Part ($)	Maximum Operations Cost per Part ($)
Concept M3	20	1.56	2.99	5.60	0.95	1.83	0.67	1.28	3.28	4.85
PBF ARCAM A1	9	1.01	1.13	5.60	0.92	1.02	0.64	0.72	5.95	6.24
PBF ARCAM A2	16	1.62	1.83	5.60	1.24	1.40	0.86	0.98	4.18	4.47
Sinter Pro DM125	4	1.53	2.62	5.60	3.15	5.40	2.20	3.78	16.22	22.23
Sinter Pro DM250	16	2.49	4.68	5.60	1.90	3.57	1.33	2.50	5.38	8.38

Figure 2d.5. Build time and cost estimates.

Material Taxonomy

A suitable material taxonomy was developed to systematically map the AM processes to materials that can be processed. Figure 2d.6 shows the AM material taxonomy.

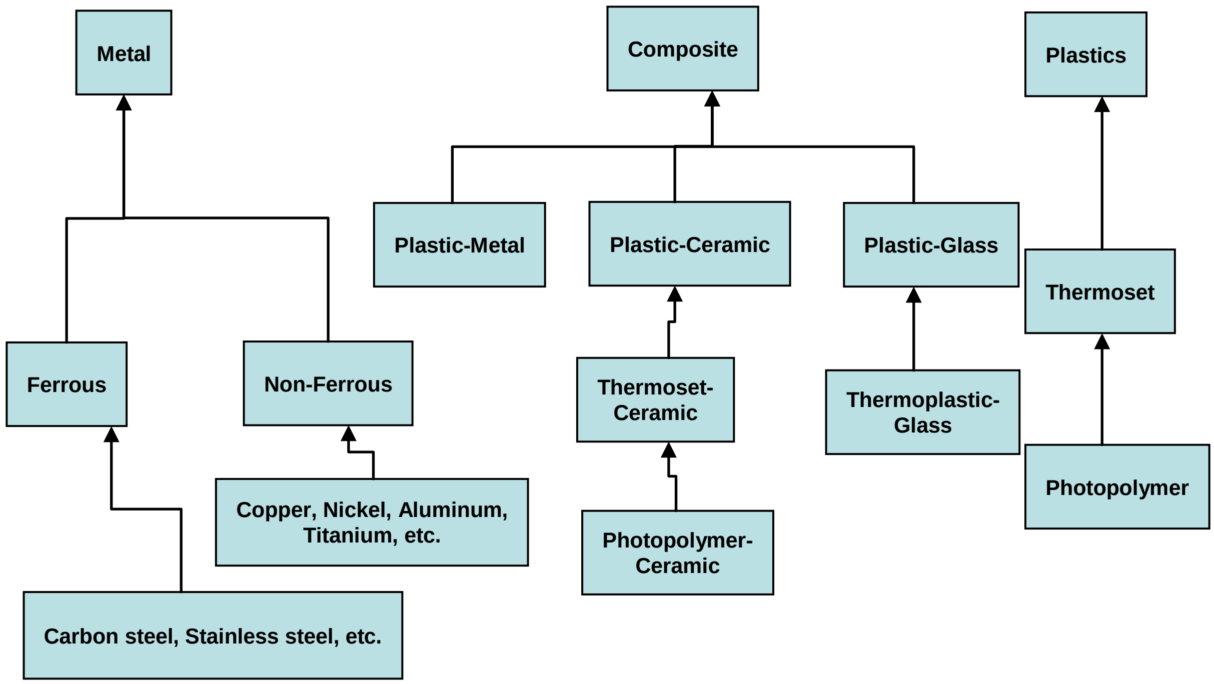


Figure 2d.6: AM Material Taxonomy.

Materials in AM are grouped into three broad categories: namely, metals, composites and plastics. Then, various material sub-categories and their hierarchical relations are identified. The AM material taxonomy in Fig. 2d.6 serves as a means to systematically identify AM materials and their types. Furthermore, such classification allows systematic development of a AM materials database.

AM Feature Taxonomy

In an effort to further characterize AM processes and machines based on geometric features, a feature taxonomy is developed for AM processes. Figure 2d.7 presents the feature taxonomy.

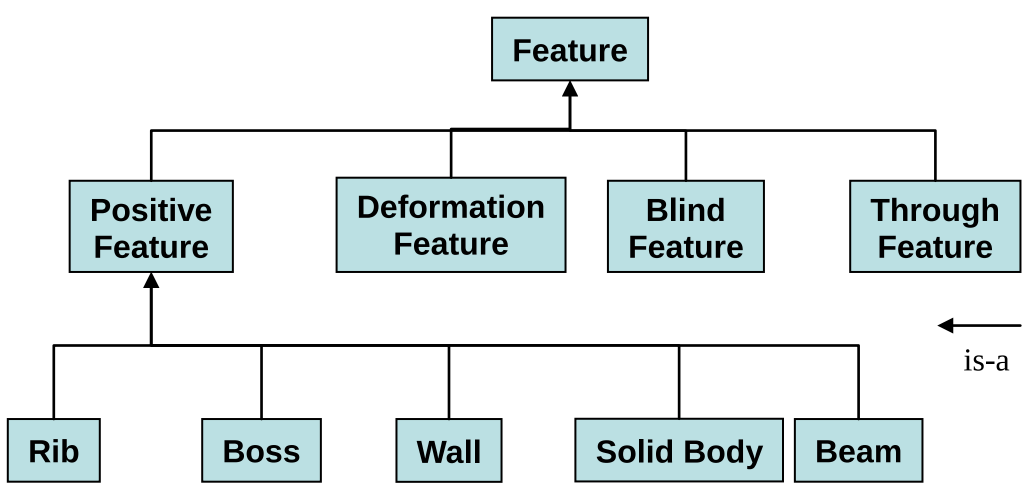


Figure 2d.7: AM Feature Taxonomy.

In Fig. 2d.7, most of the critical features, which are related to AM processes, are classified under positive features. Due to the thin layer addition technique of AM processes, AM is capable of creating virtually any shapes and features and AM always creates shapes and features as positive features. Therefore, several critical positive features are identified and classified in Fig. 2d.7. The minimum size of each positive feature can serve as an attribute for classifying different AM processes and machines.

AM Material Database

Based on the material taxonomy, a material database was generated and incorporated into the M-Library. For each material, data was obtained from a specific vendor and includes material attributes such as type, name, process, strength, etc. The type and process attributes relate specific AM process to a specific node in the material taxonomy. The AM material database can be accessed through the M-Library.

Validation of Build Time and Cost Models

To validate build time and cost models, actual build time and estimated build time were compared. Furthermore, the estimated costs of parts were compared to price quotation from a AM service bureau. To measure the actual build time, three example parts were built using three AM processes; Stereolithography (SL), Fused deposition modeling (FDM), and Ink-jet printing. The result shows that the estimations of build time and cost are reasonably accurate such that the estimation enables selection of appropriate AM processes. Details are presented in a draft paper prepared for submission to the ASME Computers & Information in Engineering Conference (see Appendix).

4.2.5 Task 2e: Characterize Welding Processes and Machines (Primary Organization Responsible: Georgia Tech MaRC, Lead: C. Ume)

The main objective of this subtask was to characterize the major joining processes used for manufacturing military ground vehicles, primarily welding processes. The primary welding processes for building military ground vehicles have been identified and object oriented process models (schemas) for the different welding processes have been developed.

Process Modeling

Table 2e.1 lists the welding processes that were modeled and implemented in the M-Library. The taxonomy of welding processes which have been modeled in the M-library is shown in Fig. 2e.1.

Table 2e.1: Welding processes modeled.

Welding Processes
Arc Welding
Flux Cored Arc Welding
Gas Metal Arc Welding
Gas Tungsten Arc Welding
Shielded Metal Arc Welding
Submerged Arc Welding
Brazing
Laser Beam Welding
Oxyacetylene Welding
Resistance Spot Welding
Soldering
Friction Stir Welding
Friction Welding
Direct Drive Friction Welding
Inertia Friction Welding
Linear Friction Welding
Radial Friction Welding
Stud Welding
Thermit Welding

The welding process taxonomy developed in this task is shown in Fig. 2e.1.

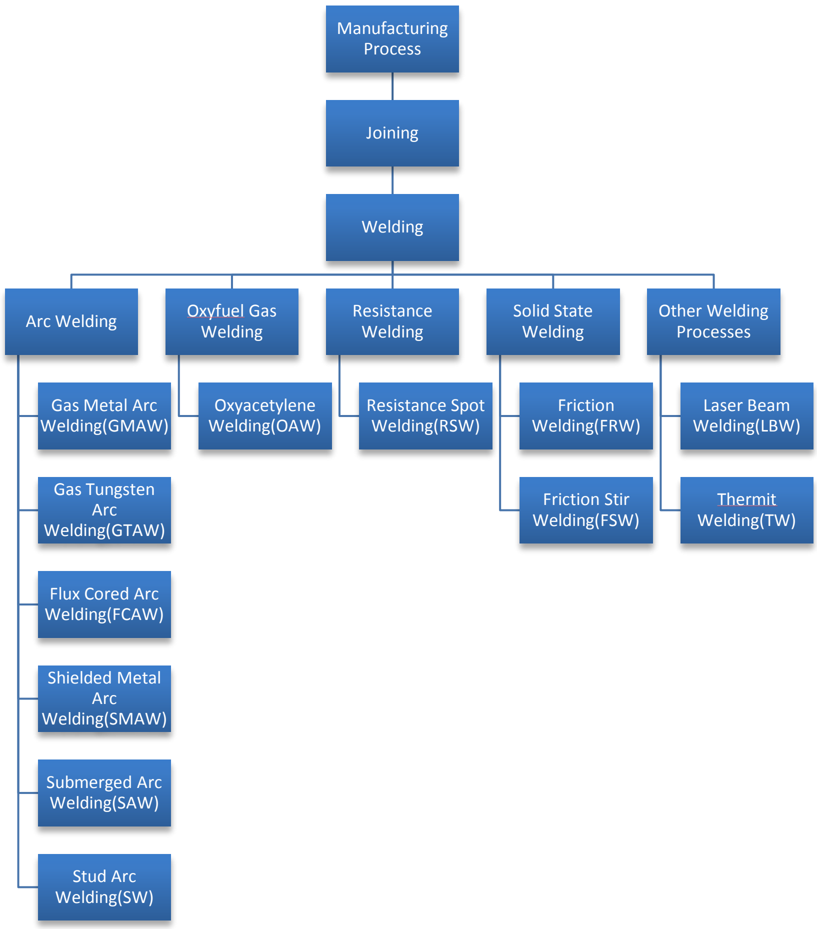


Figure 2e.1: Taxonomy of welding processes.

Different aspects of the welding processes, such as Inputs and Outputs, Machines, Tools, Fixtures & Auxiliary Resources, Operator and Facilities were characterized using appropriate properties.

The preliminary time and cost models proposed before were also further refined. Variable sources are provided along with the cost and time equations. All variables used in the models are divided into two categories, fixed properties and operational properties. Fixed properties are characterized in the M-library and directly available. Operational properties are operator or factory dependent, which is given by the end users. Default values which is the average of operational properties are also given in case of the accurate values are not available. A brief example of usage of time and cost models were also provided for demonstration.

Process - Feature Mapping

To equip the M-library with the capability to help end users select potential welding processes based on design requirements, several most important criteria were considered. Specifically, feature-process relationships, material-process relationships and shape-process relationships, which provide the feature, material and shape capabilities for each welding process, were constructed. Based on these criteria, different queries that the M-library can support were established. The weld feature taxonomy developed for this task is shown in Fig. 2e.2.

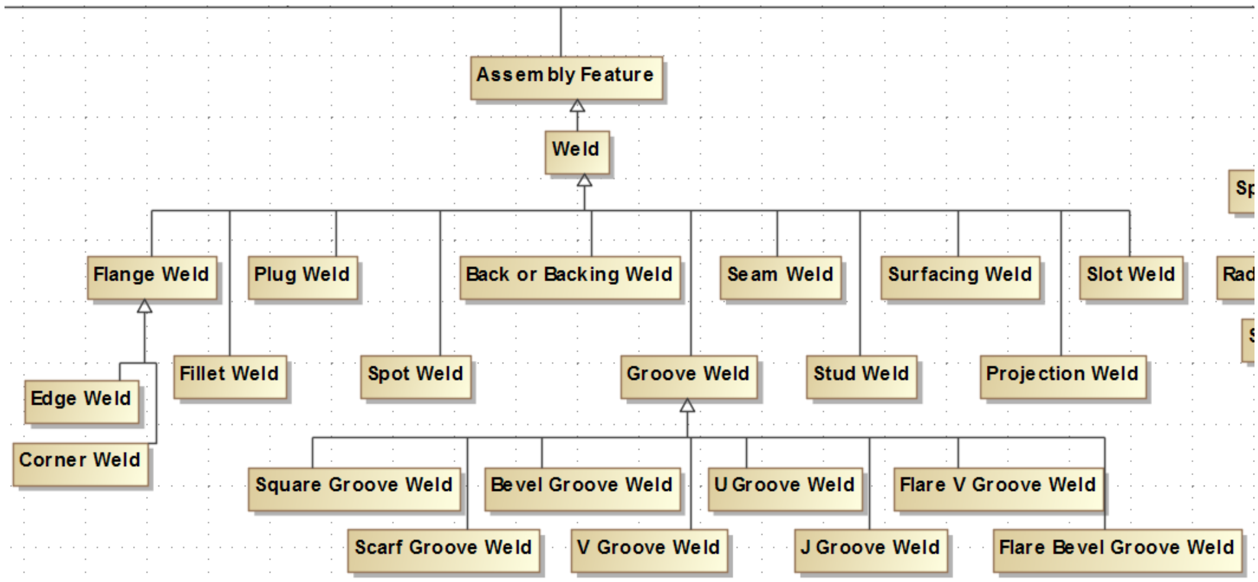


Figure 2e.2: Weld feature taxonomy.

Resource Modeling: Machines and Tools

A taxonomy of machines and other resources associated with welding processes was developed. Figures 2e.3-6 show the taxonomies of welding machines, welding tools, welding fixtures and other auxiliary resources typically required for welding. Attributes for many of the concepts contained in these taxonomies were defined and implemented.

Instances of different welding machines and tools were populated into the M-Library. Library population is a long-term process since there are so many different equipment manufacturers around the world that it is impossible to enter all available equipment information into the M-Library. Major equipment manufacturers' websites were surveyed to find out the most representative welding machines for different classes of welding applications.

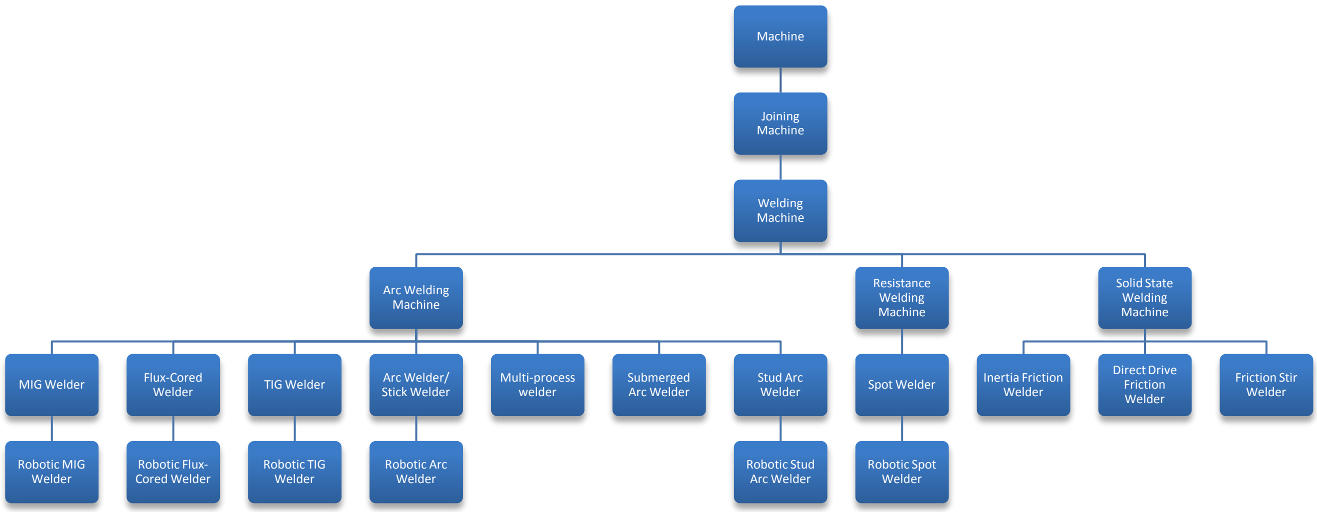


Figure 2e.3: Taxonomy of welding machines.

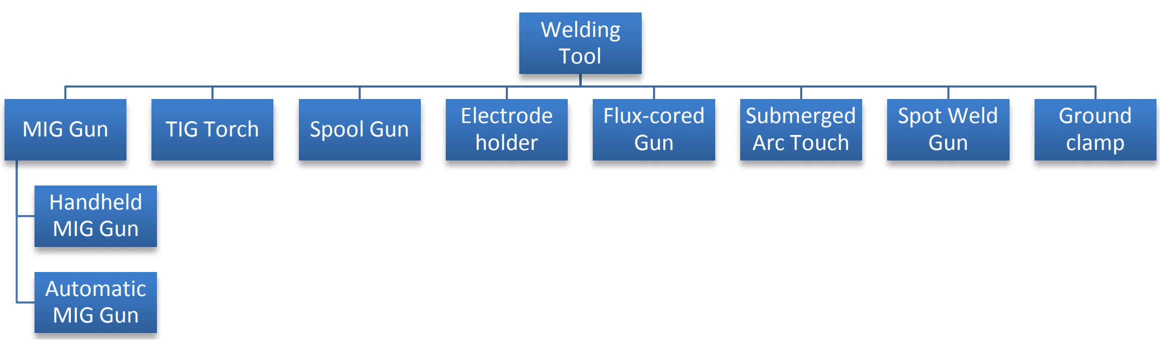


Figure 2e.4: Taxonomy of welding tools.

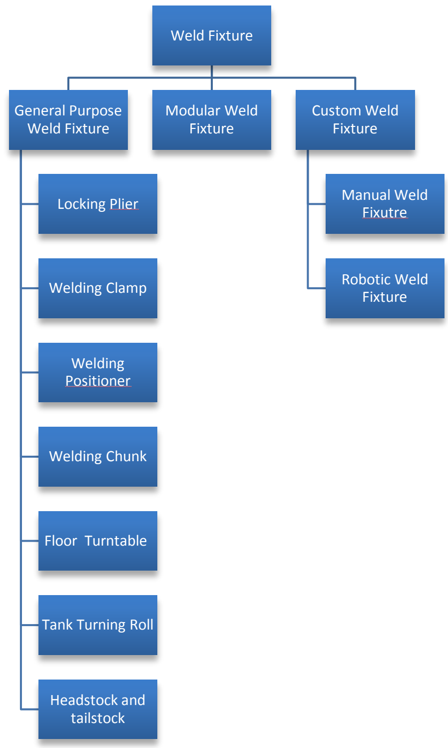


Figure 2e.5: Taxonomy of welding fixtures.

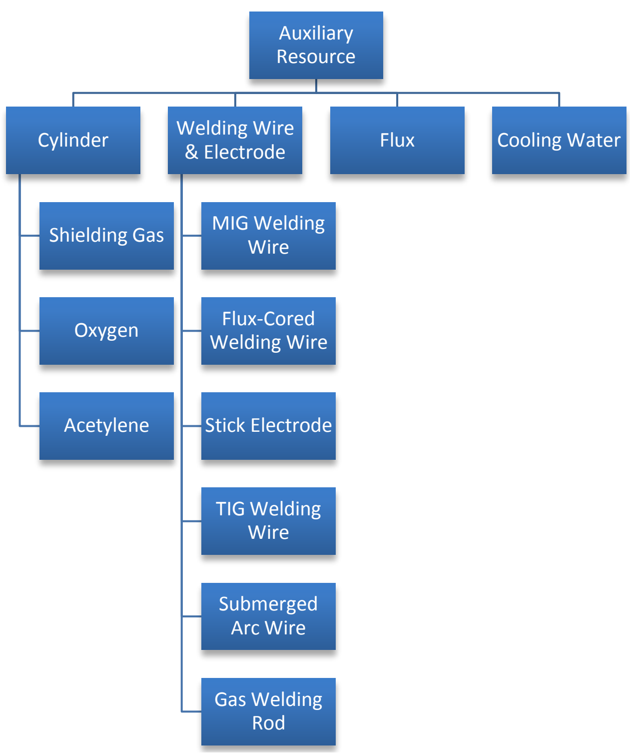


Figure 2e.6: Taxonomy of auxiliary resources for welding.

4.2.6 Task 2f: Characterize Assembly Processes
(Primary Organization Responsible: Georgia Tech MaRC, Lead: J. Morehouse)

The overall goals of the assembly task were to: 1.) identify the taxonomy of assembly processes to be included in the M-library; 2.) identify the key attributes of and characterize the assembly processes included in the library, as well as the machines and tools utilized to perform the processes; and, 3.) identify and characterize specific, commercially-available machines and tools according to the attributes chosen for inclusion in the M-library. Achievement of these goals would allow queries to be posed to the library to: (1.) identify the types of machines and tools that could be used for a given assembly operation, (2.) identify specific instances of the machines and tools available in the library, (3.) identify which machines and tools could deliver necessary performance attributes, ranging from the size of a fastener that could be installed (e.g. a 10mm socket could be used to install a particular size hex head screw) to the maximum amount of torque that the tool is capable of delivering; (4.) identify the machines and tools that could fit within a given space within an assembly to perform the required operation, (5.) estimate the amount of time required by each machine and tool to perform the assembly operation, and (6.) estimate the cost for each machine and tool to perform the assembly operation.

The following sections provide details about the major developments achieved by the assembly task. It should be noted that definitions for much of the basic terminology used throughout the assembly section of the report can be found in appendix Table 2f.A-4.

Assembly Process Taxonomy

The majority of assembly operations can be broken down into three major steps, including: (1.) alignment and clamping of two or more components for joining (e.g. mounting two components into a fixture, alignment and clamping); (2.) pre-joining operations, such as drilling holes for installation of bolts, or drilling and tapping for subsequent installation of screws; and, (3.) joining. Due to the relative importance of the joining process choice for determining important process performance attributes such as time and cost, the assembly task in this project has focused solely on joining. From the joining process taxonomy shown in Figure 2f.1 it can be seen that the term "joining" in this case is inclusive of <u>all</u> fundamental joining processes such as mechanical joining, adhesive bonding, welding, etc. and any of their respective subcategories such as installation of mechanical fasteners, integral mechanical attachments, brazing, soldering, etc..

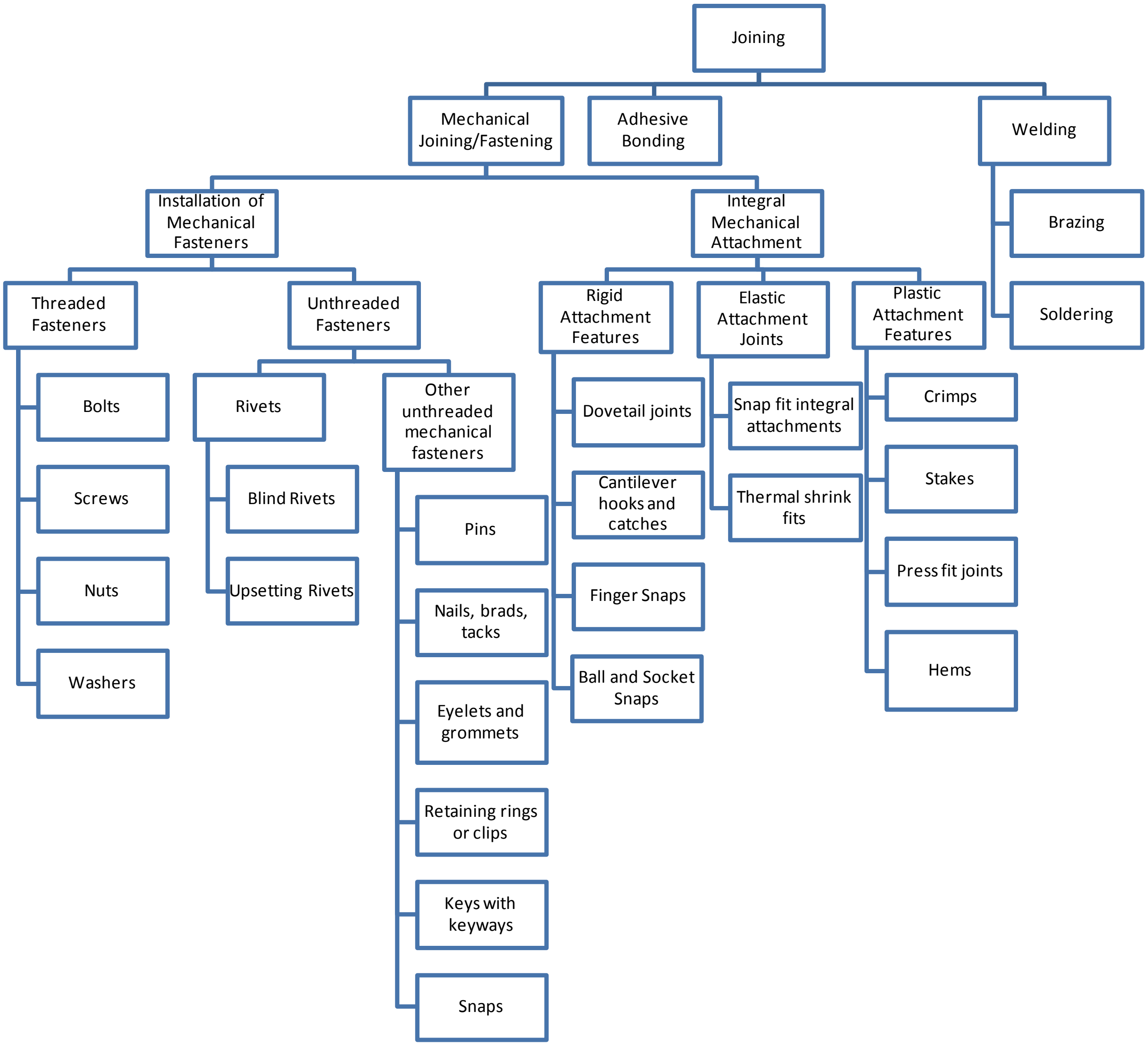


Figure 2f.1: Taxonomy of common joining processes used in assembly processes.

Due to their importance in the assembly of armored ground vehicles, installation of threaded fasteners became the focus of detailed characterization for the assembly task 2f and will be discussed in detail below. Detailed characterization of welding processes, which are also common in the assembly of armored vehicles, was carried out in the welding task 2e. In addition, several of the processes shown in Figure 2f.1 have been included in the M-library as placeholders (where detailed characterization was not completed in this task) in order to make the library easily expandable for future users.

Taxonomy of Machines and Tools used for Installation of Threaded Fasteners

As mentioned above, mechanical fastening using threaded fasteners was the joining process chosen for detailed characterization in the assembly task. Several handheld machine and tool types commonly used for installation of threaded fasteners were identified and categorized according to the basic sample taxonomy shown in Figure 2f.2 (note that several additional subcategories of machines and tools are included in the M-Library). The taxonomy is made up of “fastening tools” and “fastening machines”. Fastening tools are defined as any tool that makes direct contact with the fastener for installation. Examples include manual hand held tools such as adjustable wrenches, combination wrenches and screwdrivers which can be used independently to install a fastener, as well as socket wrenches, screwdriver bits, screwdriver socket bits, etc., that necessitate the use of an attached fastening machine to drive them.

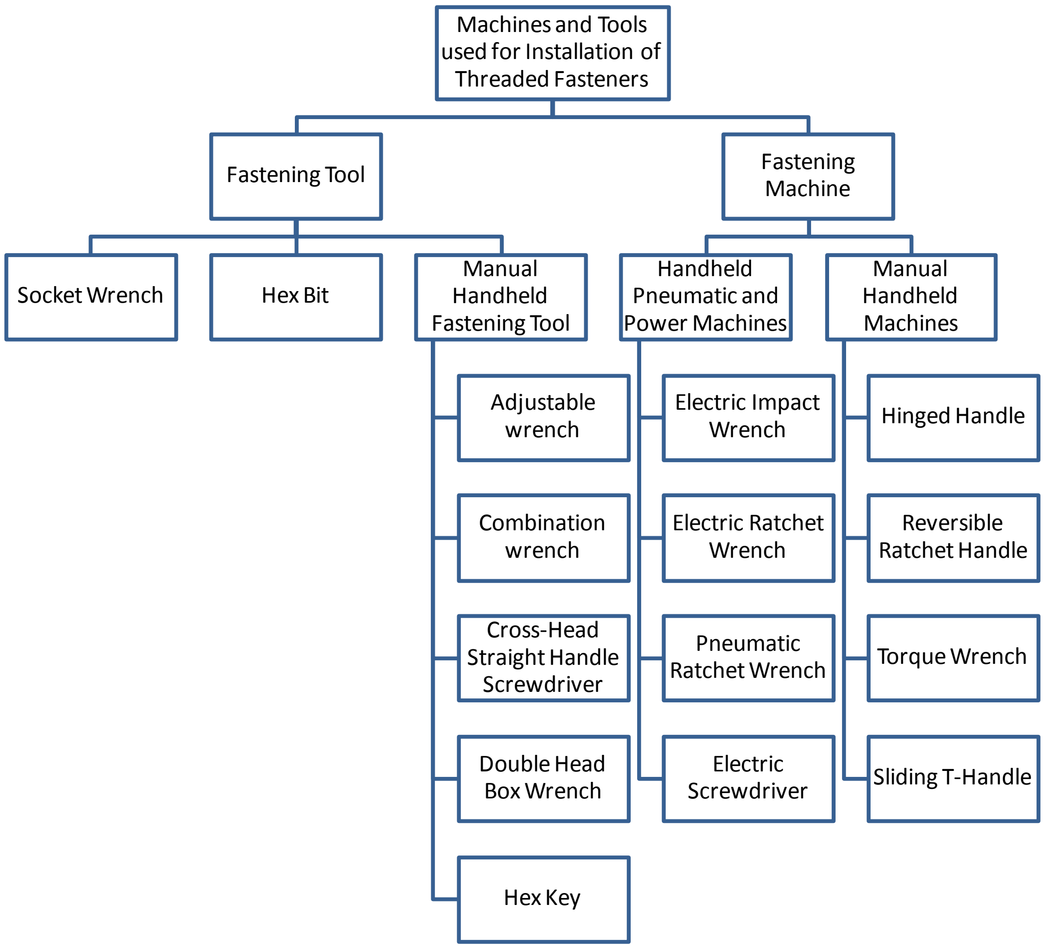


Figure 2f.2: Taxonomy of several machines and tools used for installation of threaded fasteners. Note that the M-library includes many additional machine and tool types.

Fastening machines are broken into the two main types of “Handheld Pneumatic and Power Machines” which are - as the name suggests - powered by compressed air or electricity but are still handheld, and “Manual Handheld Machines” which are actuated manually by operators. Both fastening machine types require an attached “fastening tool” (e.g. socket wrench, screwdriver socket bit, etc., which makes contact with the fastener as explained previously) to install the fastener.

Threaded Fastener to Tool Mapping and Tool to Machine Mapping

Several ANSI/ASME standard fastener types consisting of bolts, screws, machine screws, nuts, and washers, were identified for inclusion in the M-library. The fasteners were named according to the designation provided by the relevant ANSI/ASME standard for the particular fastener. Appendix Table 2f.A-1 shows the complete listing of the fasteners identified for inclusion in the library, along with the pertinent standard for each, and highlights in yellow all fasteners that are currently implemented in the software.

Based on the drive type of each fastener a mapping was established between the fastener and the tools in the library that could be used to install it. For example, a metric socket head cap screw has a hex socket drive. Consequently all tools that can actuate this drive type (i.e. a hex key, hex socket bit, and hex bit) were identified and mapped to the socket head cap screw in the software. Appendix Table 2f.A-2 shows the mapping of all identified fasteners to the Manual Handheld Fastening Tools that exist within the library while Appendix Table 2f.A-3 displays the mapping of all identified fasteners to the Fastening Tools that exist within the library. All fasteners that currently exist in the library are once again highlighted in yellow although all identified fasteners are included so that future library users can add the additional fasteners along with the appropriate tool mapping.

All Fastening Tools such as socket wrenches, flat tip screwdriver socket bits, hex socket bits, etc. were also mapped to the Fastening Machines with which they can be used by using a machine-tool taxonomy approach. Figure 2f.3 shows an illustration of a reversible ratchet handle and the associated machine-tool mapping.

Reversible ratchet handle for use in driving socket wrenches. Source: ANSI/ASME B107.10-2005

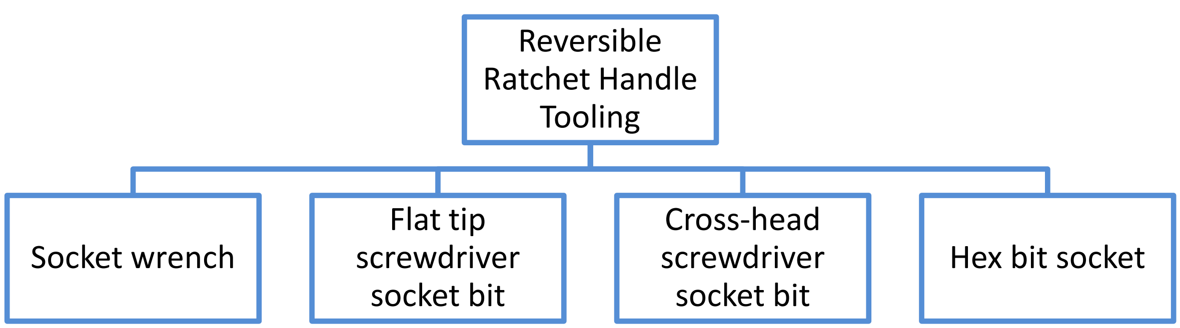


Figure 2f.3: Taxonomy of tooling in the M-library that can be used with a reversible ratchet handle.

As can be seen from the Figure, the tools within the library that could be used with a reversible ratchet handle are socket wrenches, flat tip screwdriver socket bits, cross-head screwdriver socket bits, and hex bits. A similar mapping procedure was used for all machines and tools that exist within the library.

Characterization of Machine and Tool Types for Threaded Fastener Installation

Attributes specific to machines and tools used for threaded fastener installation were identified and added to the M-library using the knowledge capture process and subsequent iterations with InterCax. The attributes that were identified as most important for inclusion were those that would have an impact on machine or tool selection for a given assembly. It was determined that the identification of potential tools that could be used for installing fasteners in a particular assembly would be highly dependent on key factors such as: 1.) the amount of space that a particular tool will occupy around the fastener; 2.) the maximum speed at which a machine or tool can be operated – which will ultimately govern cost; 3.) the maximum torque that the tool can deliver comfortably by an operator and before failure of the machine or tool occurs; 4.) the nominal size of the fastener to be installed (e.g. a 1/8" Hex Bolt); and, 5.) the nominal size of the drive for a fastening machine or tool (e.g. ¼" drive socket wrench). Figure 2f.4a shows a screenshot from the MaCME interface which shows all attributes associated with a generic "Fastening Machine" in the M-library. It can be seen that general attributes such as model id, degrees of freedom, compressed air requirement, etc., have been inherited. However, attributes related to some of the key threaded fastener installation factors discussed previously such as "drive shape," "drive type", "nominal size" etc. have been added.

Figure 2f.4a: Screenshot from macme interface which shows several of the attributes associated with a generic Fastening Machine in the M-library.

Detailed characterization of several commercially-available fastening machines and tools was performed using data gathered from manufacturer or distributor websites or catalogues. Several of the key attributes discussed in the previous section were populated for each machine and tool instance in addition to the general dimensional data, manufacturer and model id information, etc.. In total, more than 100 fastening machines and tool instances have been populated in the library.

It should be noted that some key assumptions were made in populating some of the data in the library. For example, the "working torque range max." value for manual handheld tools is calculated by assuming that the operator applies a 20lbf force at a distance equal to the overall length of the tool. This may be a reasonable assumption if the tool is used in areas with little or no space constraints where the operator is free to place his/her hand where she chooses but could break down when modeling assembly in tighter spaces. The data for "wrench clearance required-z" for hand tools was estimated by doubling the thickness of the head for box-end wrenches in order to account for the need for the box end to completely clear the top of the fastener before it can be installed. For open-end wrenches, however, the thickness of the head was simply used since the wrench can be slid on the fastener from the side – it does not need to clear the top of the fastener head since it has an open end.

Both of the assumptions mentioned above point to the need for further work to refine the library's capabilities. Specifically, operator performance and ergonomics analysis capability could be integrated with the software in future revisions so that for each unique assembly that is being modeled a realistic estimate of applied torque could be made. The importance of accurate modeling of applied torque will become evident when a process planner or manufacturing engineer is trying to select the best machine or tool for the job.

Available clearance for a machine or tool within a given assembly can only be accurately modeled using three-dimensional CAD models of both the fastening machine or tool and the assembly. Collision detection using both models needs to be performed to eliminate the error born by the assumptions made. Several commercially available manufacturing modeling software packages such as DELMIA by Dassault Systemes, and Process Simulate by Seimens could be used for this purpose. It was hoped that a seat of one of these software packages could be purchased for this project, however, both were cost-prohibitive.

Finally, it should also be noted that not all attributes for assembly machines and tools were populated when adding instances to the library. This is due to the lack of (or difficulty in obtaining) information from the machine and tool vendors. However, further revisions of the library may significantly pare down the number of attributes that are needed for adequate modeling of the assembly process and several attributes could be removed.

Time and Cost Models for Installation of Threaded Fasteners

A first order time estimation model for installing threaded fasteners was created and is shown below in Equation 2f.1. The model uses the pitch (for metric fasteners) and the installation length of the thread in the assembly to calculate the total number of revolutions the fastener will complete during installation. Note that the thread installation length is the length of the threaded portion of the fastener which will be engaged in the component after installation. Dividing this number by the maximum RPM of the tool used for installation gives the estimated installation time. Cost is calculated by using the installation time and pertinent hourly labor and burden rates.

Time = (1/pitch)*(Thread Installation Length in Assembly)/RPM (Equation 2f.1)

The maximum rpm for most pneumatic and electric powered fastening machines can be found in the product literature. However, for manual hand held machines such as ratchet wrenches, as well as handheld fastening tools such as combination wrenches, it was necessary to estimate typical RPM values. Simple time studies were performed in the office environment to obtain an estimate of how long it would take to move a manual machine or tool through a complete revolution. Factors such as the need to remove a box wrench from a screw or nut before resetting the wrench on the fastener for the next revolution (e.g. when there is not enough space for a full revolution) were considered. A list of the estimated times to make a revolution using several of the machines and tools in the library is provided in Appendix Table 2f.A-5.

A more accurate estimation of the RPM of manually activated hand tools could be obtained using motion study standard data, such as the data contained in the MTM time standards. To this end, Proplanner Inc.'s ProTime software was purchased as part of the project. The software was delivered much later than expected and at the time of the writing of this report time studies are still being constructed within the software. However, the overall principle (i.e. using time standards to estimate installation speeds with manual handheld tools) could be utilized in future releases of the M-library to obtain more realistic time data and more accurate comparisons of assembly machines and tools in terms of threaded fastener installation time.

Mechanical Joining Process Feature Mapping

Mechanical joining process feature mapping was performed in order to identify and simplify the key inputs and outputs of mechanical joining processes, which could ultimately be used in mechanical joining process selection. In terms of process outputs three basic assembled joint types, which are correlated with assembly loading conditions, were identified based on work done by Messler [Messler, 2004]. As shown in the feature taxonomy in Figure 2f.4, the key joints that can be produced by mechanical joining processes fall into the basic categories of shear loaded joints, tension-loaded joints, or some combination of the two.

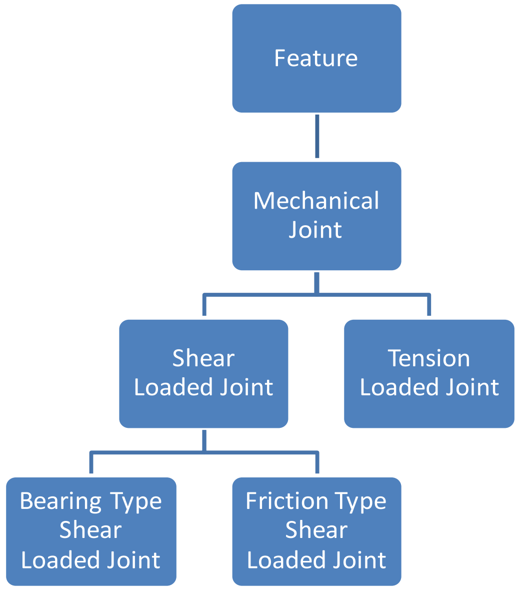


Figure 2f.4b. Taxonomy of essential features (joints) produced by a mechanical joining process.

There are two major subcategories of shear loaded joints including bearing-type shear loaded joints and friction type shear loaded joints. Appendix Figure 2f.A-3 shows an illustration of each joint type while Table 2f.A-2 provides a mapping of the joint type that can be produced by several mechanical joining processes.

Further characterization of the typical inputs to mechanical joining processes was also performed. Table 2f.A-3 shows a mapping of several major material categories that can be assembled using various mechanical joining processes. Input shapes were also considered for several mechanical joining processes. It should be noted that components of an infinite number of shapes can be assembled using mechanical joining processes. However, for joining to take place there will be constraints on the shapes of the mating areas of the components (e.g. flat, rectangular surfaces present on two components will produce a suitable mating area for mechanical fastening). Table 2f.A-4 lists several mechanical joining processes and the allowable shape codes (based on Ashby's shape classification system) of the mating areas of two components for each process, as well as notes and examples for each range of potential shape codes.

All of the input/output feature mapping work discussed above could be very useful in future implementations of the M-Library as a guide for selecting suitable mechanical joining processes given a pair of components to assemble. For example, given two parts made of aluminum with flat, rectangular mating areas, through implemented mechanical joining feature maps the M-library could tell us that threaded fasteners, rivets, and pins could be used to successfully join the components provided that the resulting joint is loaded in shear. Similarly, if both or one of the components is made of a ceramic, the list of potential mechanical joining processes is limited to just threaded fasteners. Thus, given further development, the M-library could eventually be used as an assembly process selection guide by manufacturing engineers or designers.

Demonstration of the Assembly Process Capabilities of the M-Library

An assembly exercise was given to the Georgia Tech team so that the capabilities of the M-Library could be demonstrated at the March 2012 AVM PI meeting. The front right hub assembly, shown in blue as part of the vehicle assembly in Figure 2f.5, and a more detailed view in Figure 2f.6, was chosen as the assembly to use for demonstration due to its relative complexity, variety of fastener types, as well as the space constraints provided by one of the fasteners.

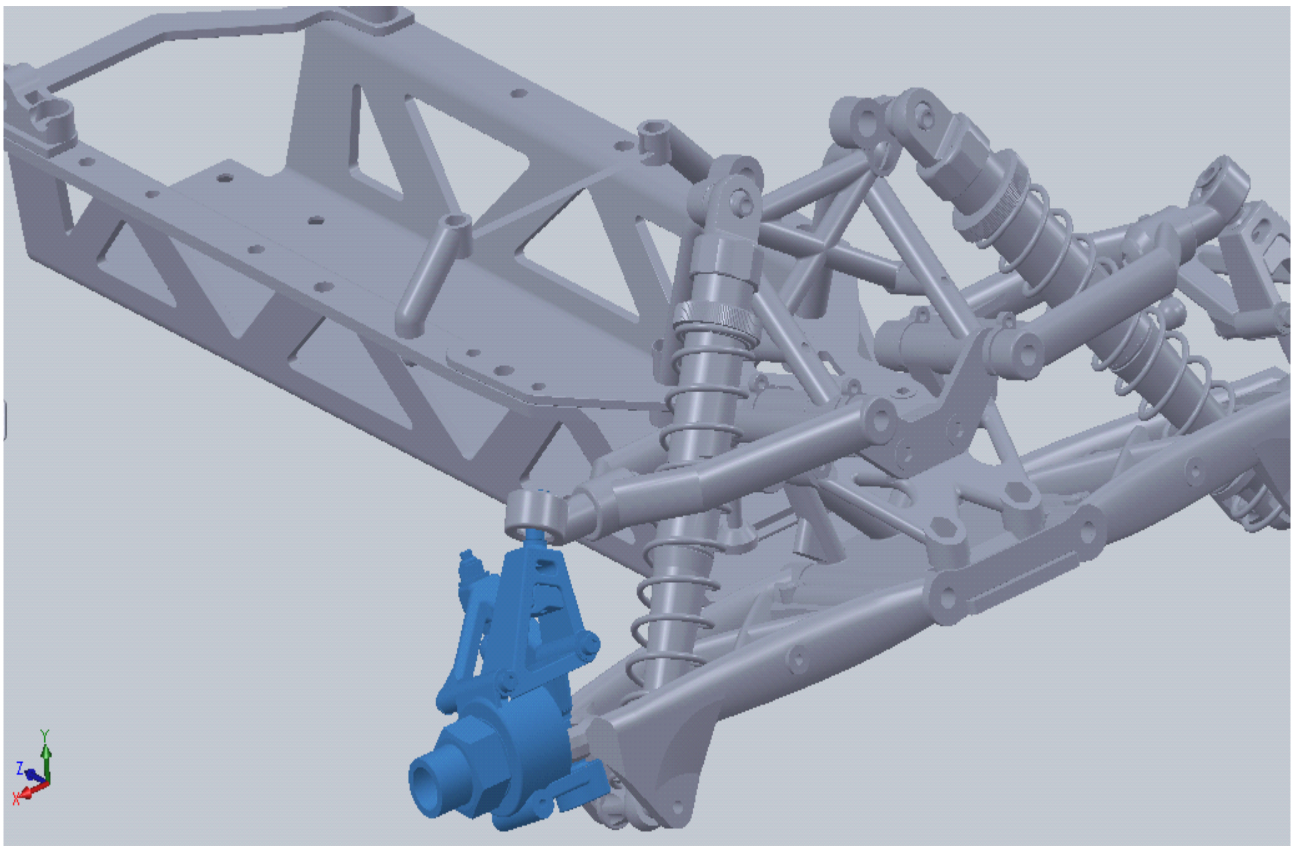


Figure 2f.5. Front right hub assembly shown in blue as part of the complete vehicle assembly.

To prepare for the assembly demonstration, all fastener types were identified using the CAD models and bill of materials provided by the Meta team. Several test queries were subsequently run in MaCME to show that the software was able to: (1.) identify the types of machines and tools that could be used to install each fastener in the assembly, (2.) identify the machines that could be used with the tools identified in the first query, (3.) identify specific instances of the machines and tools in the library, (4.) identify which machines and tools could provide the specified torque level, (5.) identify the machines and tools that could fit within a given z-clearance (parallel to the fastener axis) around the fastener within the assembly, and (6.) estimate the amount of time required by each machine and tool to install the specific fasteners. All of these capabilities were successfully demonstrated at the PI meeting.

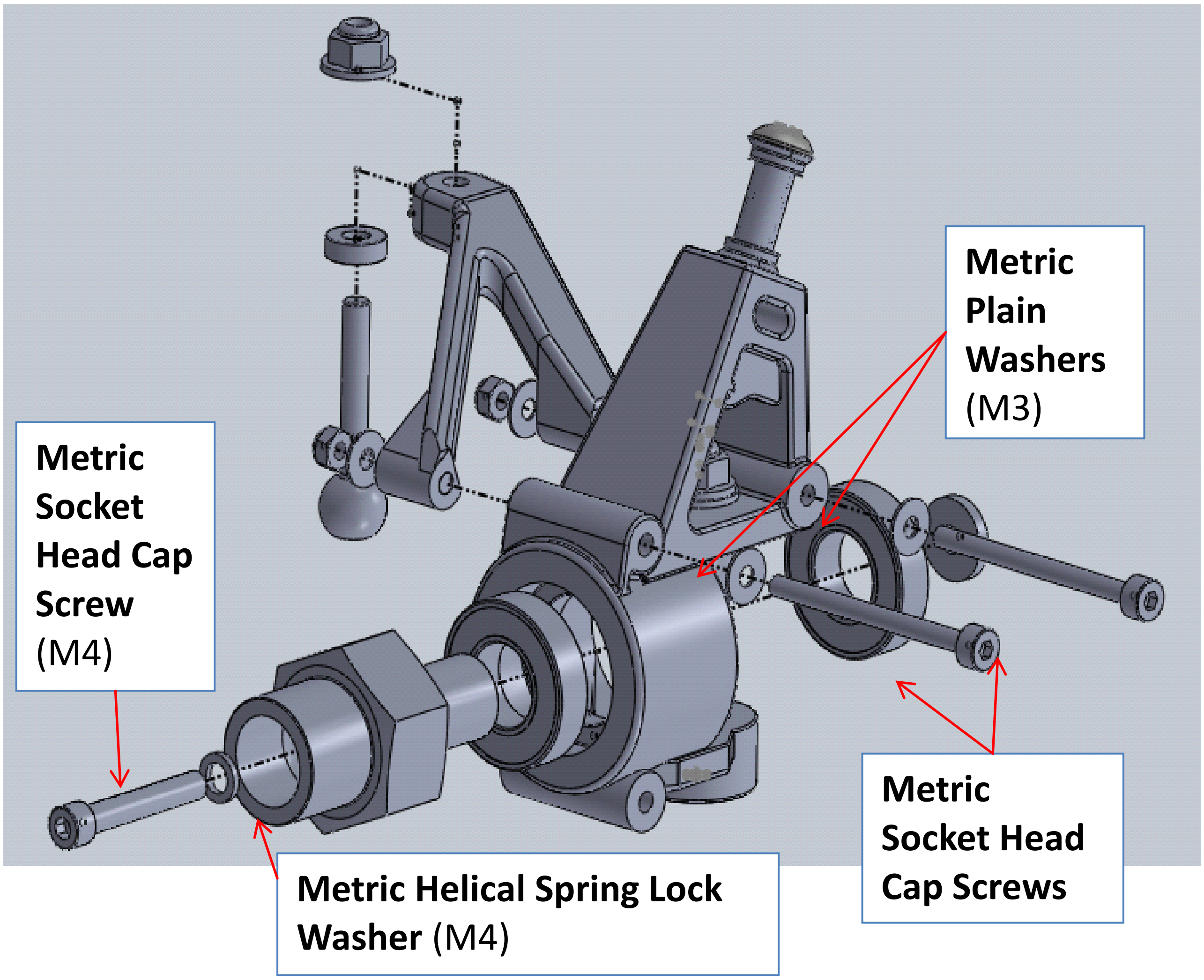


Figure 2f.6. Front right hub assembly shown in detail with fasteners identified.

References

Messler, R. W. (2004). Joining of materials and structures: from pragmatic process to enabling technology. Amsterdam: Elsevier.

Messler, R. W. (2006). Integral Mechanical Attachment: A Resurgence of the Oldest Method of Joining. Butterworth-Heinemann.

Oberg, E., McCauley, C. J. (2004). Machinery's handbook: a reference book for the mechanical engineer, designer, manufacturing engineer, draftsman toolmaker and machinist. 27th ed. New York: Industrial Press.

Shigley, J. Edward. (2004). Standard handbook of machine design. 3rd ed. New York: McGraw-Hill

4.2.7 Task 2g: Characterize Surface Finishing Processes (Primary Organization Responsible: Georgia Tech MaRC, Lead: R. Cowan)

This sub-task seeks to characterize the quantitative and qualitative attributes of surface finishing processes.

Process Modeling

A broad range of industrial processes that alter the surface of a manufactured product to achieve a desired property were evaluated and submitted for M-Library incorporation. Relevant surface finishing operations have been classified as noted in Table 2g.1

Table 2g.1: Surface finishing operations

Machining Processes (subtractive)	Surface Treatments (neutral)	Platings/coatings (additive)
1.Deburring	1. Anodizing	1. Electroplating
2. Honing	2. Heat treating	2. Air spray painting
3. Polishing	3. Shot peening	3. Chemical vapor deposition
		4. Polyurethane coating
		5. Thermal spraying

A sample of the subtractive finishing processes taxonomy is shown in Fig. 2g.1.

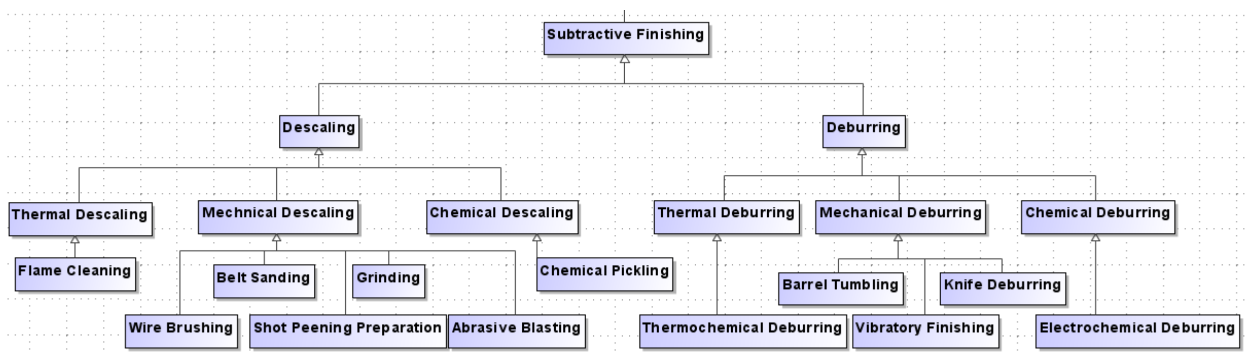


Figure 2g.1: Taxonomy of subtractive finishing processes.

Resource Modeling: Machines

Detailed attribute-based models of a select number of finishing machines were developed and implemented in the M-Library. Figure 2g.2 shows the machine taxonomy that was implemented.

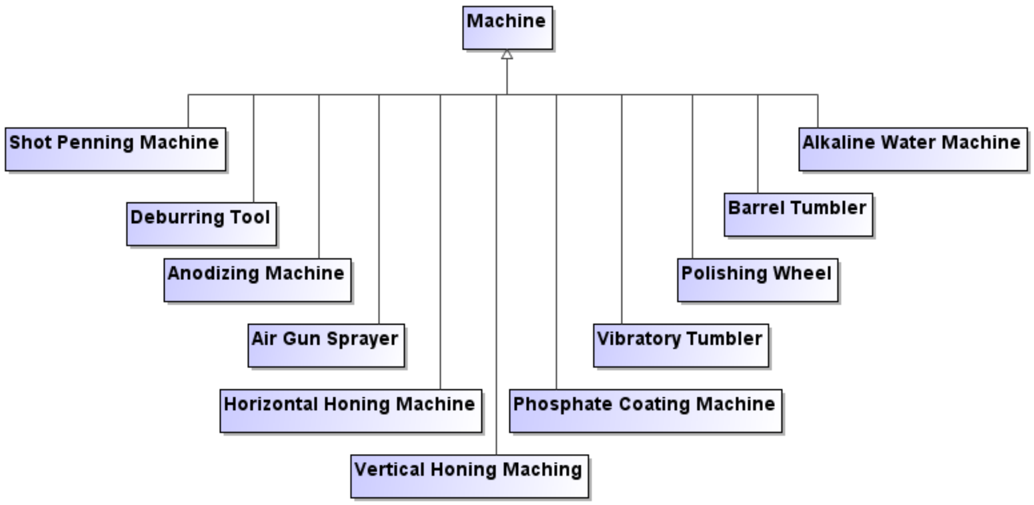


Figure 2g.2: Finishing machines taxonomy.

4.3 Task 3: Manufacturing Knowledge Modeling
(Primary Organizations Responsible: InterCAX & Georgia Tech MaRC,
Lead: M. Bajaj, D. Zwemer)

The goal of Task 3 of the DARPA iFAB project was to design and develop MACME and M-Libraries. In this section, a brief introduction of the Manufacturing Capability Modeling Environment (MACME) is presented.

MACME is a model-based systems engineering environment for enabling rapid (re)configuration and development of manufacturing processes for armed military ground vehicles. The conceptual architecture of MACME is shown in Figure 3.1. It is is a collection of meta-models, databases, and software capabilities related to the M-Library.

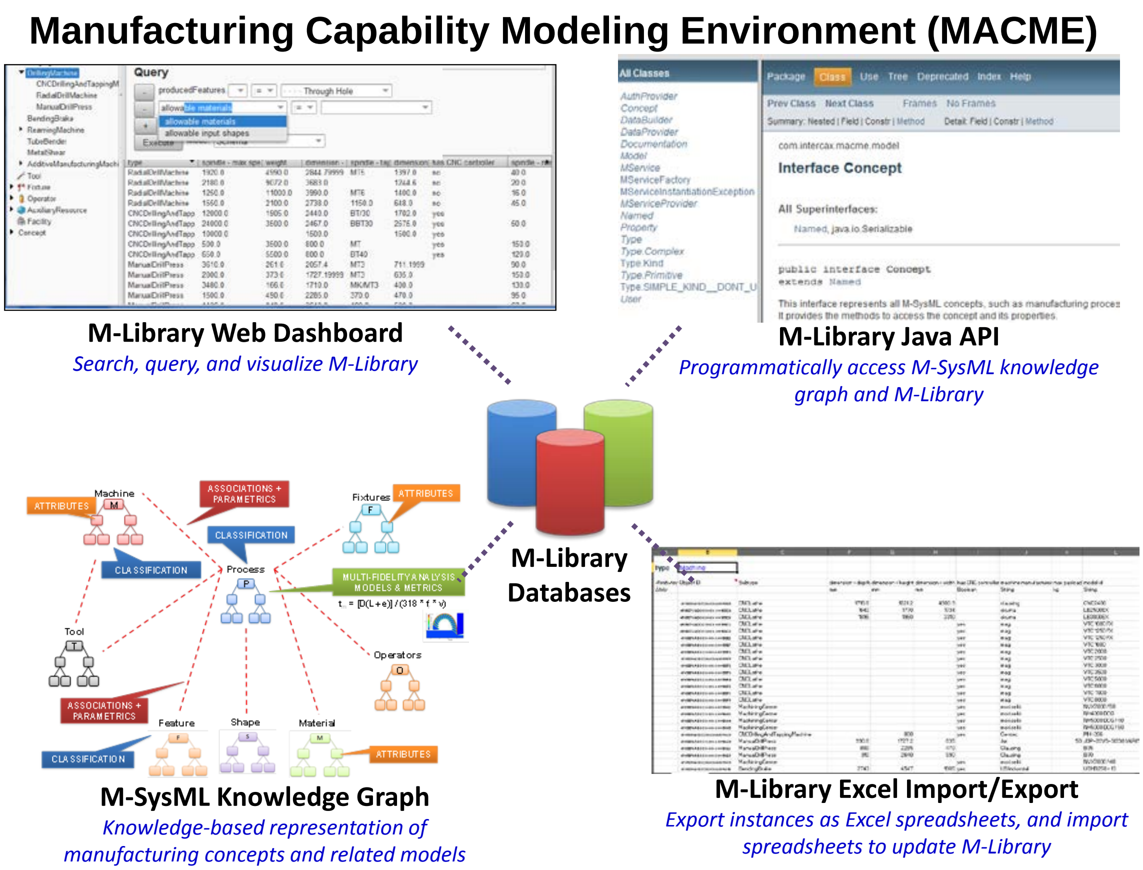


Figure 3.1: Manufacturing Capability Modeling Environment (MACME).

The components of MACME are as follows:

1. **M-Library** is a library of reusable, composable, and executable manufacturing system building blocks, such as processes, machines, tools, fixtures, operators and facilities that can be used to synthesize, analyze, and optimize process plans. The primary goal of the Georgia Tech iFAB project was the development of M-Library. MACME is a software environment, including M-Library, for design, development, validation, access, and

maintenance of M-Library. The library is stored and managed in an instance of MongoDB – an object-oriented database.

2. **M-SysML Language** is the manufacturing domain-specific modeling language that provides the constructs for representing: (a) semantic knowledge about manufacturing processes and related elements, (b) prediction models of manufacturing processes, such as those for predicting time, cost, and feasibility of processes, and (c) queries posed on M-Library. The M-SysML language is the ontology for the M-Library.

3. **M-Library Web Dashboard** is a web application that allows users to browse, search, visualize, and export/import instances from/to the M-Library database. The dashboard provides a query capability using which iFAB process planners and META designers can query the M-SysML knowledge graph and the M-Library database. Queries can be composed from multiple criteria, each of which can be described using the properties of concepts encoded in M-SysML.

4. **M-Library Excel Import/Export** capability allows users to download instances of any M-SysML concept as Excel spreadsheets. Users can add/modify the spreadsheets and import back into the M-Library.

5. **M-Library Java API** provides Java interfaces to programmatically access the M-Library. Developers of process planning and synthesis algorithms can use the API to query both the M-SysML knowledge graph and concept instances in the M-Library database.

4.3.1 M-SysML

M-SysML is a manufacturing domain-specific modeling language, based on OMG Systems Modeling Language international standard, that provides the constructs for representing: (a) semantic knowledge about manufacturing processes and related elements, (b) prediction models of manufacturing processes, such as those for predicting time, cost, and feasibility of processes, and (c) queries posed on M-Libraries. As shown in Figure 3.2 below, M-SysML is a knowledge graph that contains detailed taxonomies of manufacturing processes and related concepts such as machines, tools, fixtures, facilities, operators, and products; the attributes that characterize these concepts; the fine-grained relationships between these concepts (across taxonomies) at different levels of abstraction; and multi-fidelity analysis models for analyzing time, cost, and other measures-of-effectiveness of processes. Figure 3.3 shows the M-SysML knowledge graph model in MagicDraw SysML authoring tool.

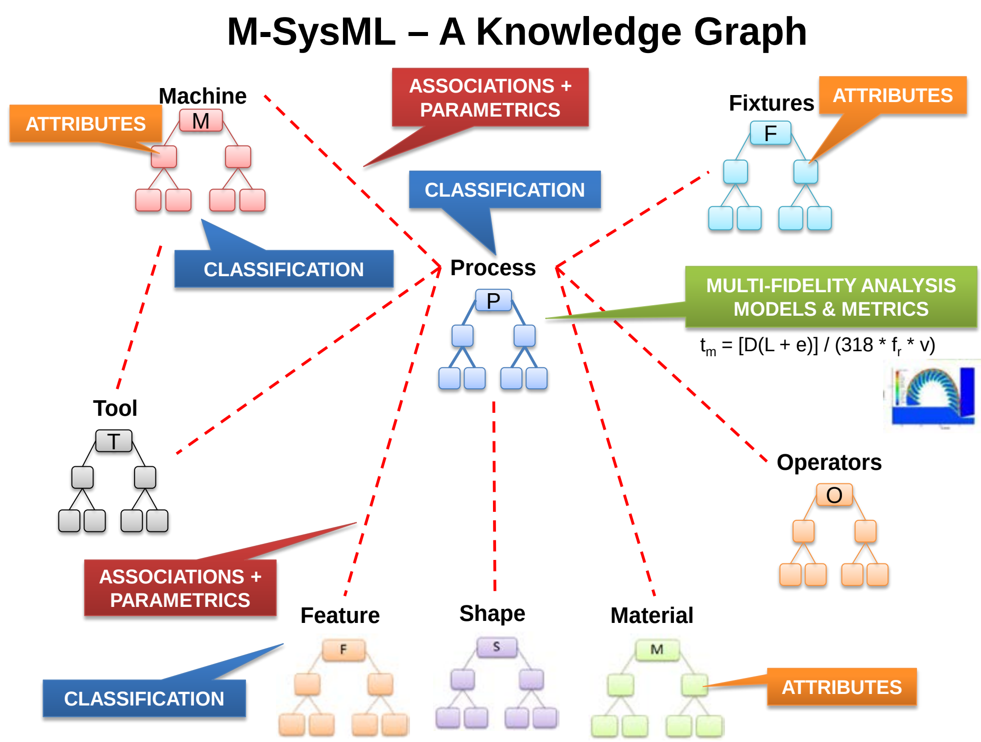


Figure 3.2: M-SysML is a knowledge graph of manufacturing concepts.

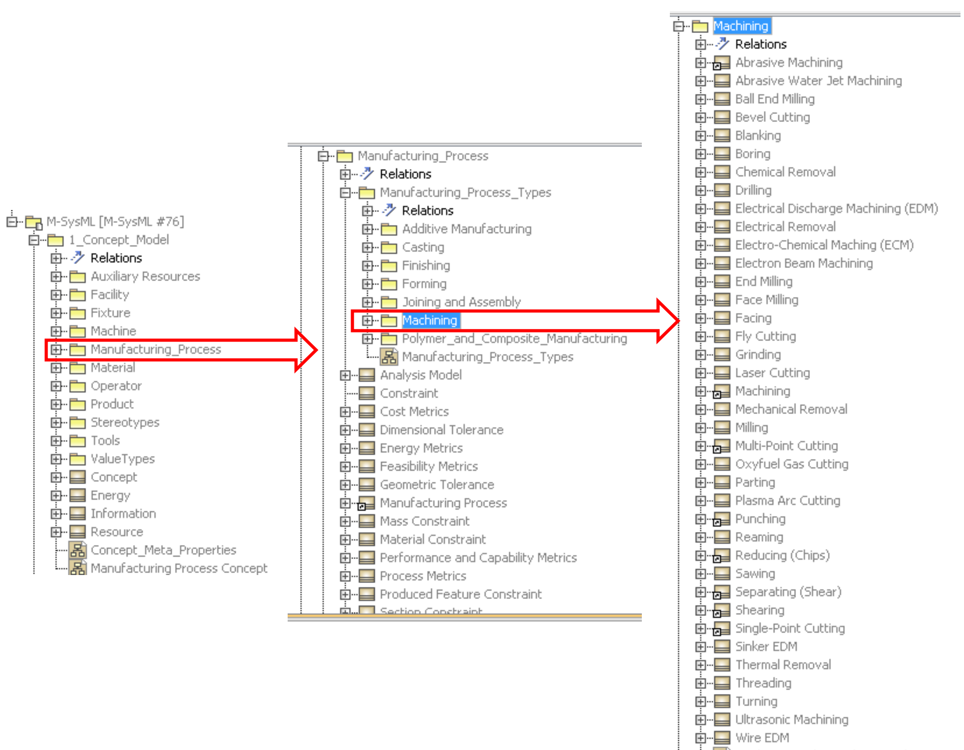


Figure 3.3: M-SysML Concept Model – SysML model containment view in MagicDraw.

Table 3.1 presents manufacturing process coverage in the M-Library. Overall, the library contains models of 209 processes (including abstractions). Table 3.2 presents key statistics about the M-Library in terms of the types of concepts such as processes, machines, tools, and fixtures; as well as number of concepts instances (e.g. machine instances). The iFAB effort focused on developing an approach to add/modify/remove instances from the M-Library and demonstrating this approach for real machine instances. This goal has been successfully achieved. The iFAB Foundry performer will use this approach to populate resources necessary for the FANG challenges.

Table 3.1: M-SysML process coverage

Additive Manufacturing	8
Casting	6
Finishing	76
Forming	30
Joining and Assembly	34
Machining	37
Polymer & Composite Manufacturing	17
Total number of processes	**209**

Table 3.2: M-Library statistics

Types of concepts in M-Library	
Types of processes	142
Types of machines	184
Types of tools	71
Types of fixtures	29
Types of product features	59
Types of fasteners	54
Total number of concepts	*747*
Instances of concepts in M-Library	
Number of machine instances	*524*
Number of material instances	*314*

Manufacturing Process concept

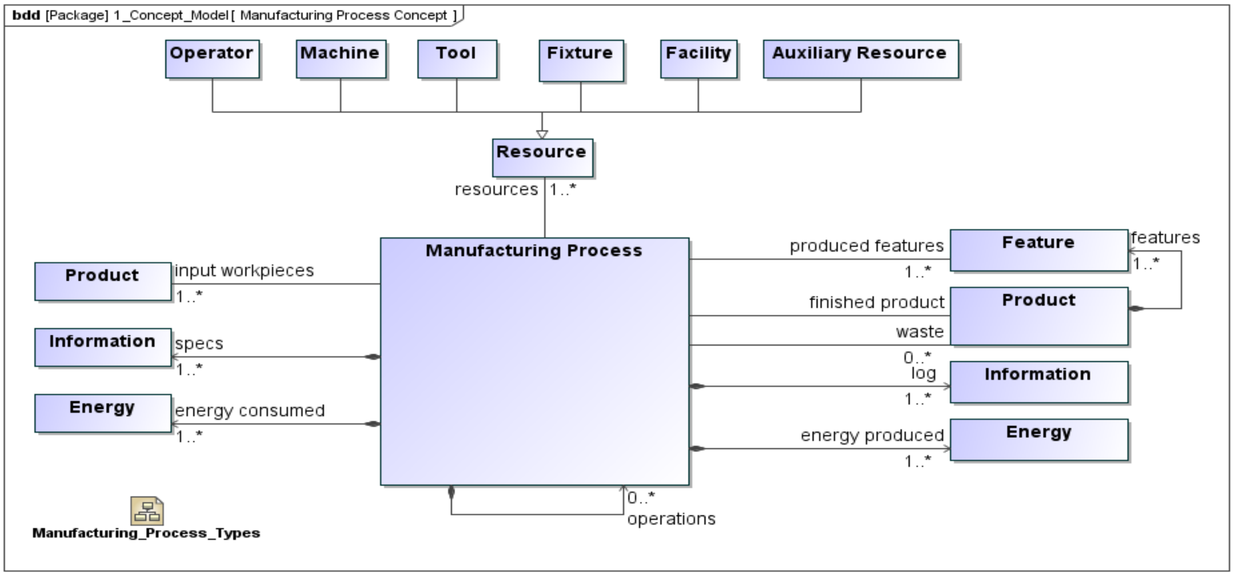


Figure 3.4: High-level view of manufacturing process and related concepts in M-SysML

Figure 3.4 is a SysML block definition diagram illustrating the top-level characterization of a manufacturing process. A manufacturing process transforms one or more workpieces to a finished product, creating one or more product features. In M-SysML, a manufacturing process can be a unit-level process or composed of multiple operations where each operation can be a complex manufacturing process itself. A manufacturing process uses resources to achieve this transformation. Operators, machines, tools, fixtures (for work pieces), facilities, and auxiliary resources (such as cutting fluids) are the different types of resources used by a manufacturing process. In addition, a manufacturing process uses energy and information (process goals and operational instructions) to achieve this transformation, and also produces energy and product waste, and new information (such as process logs and sensor data).

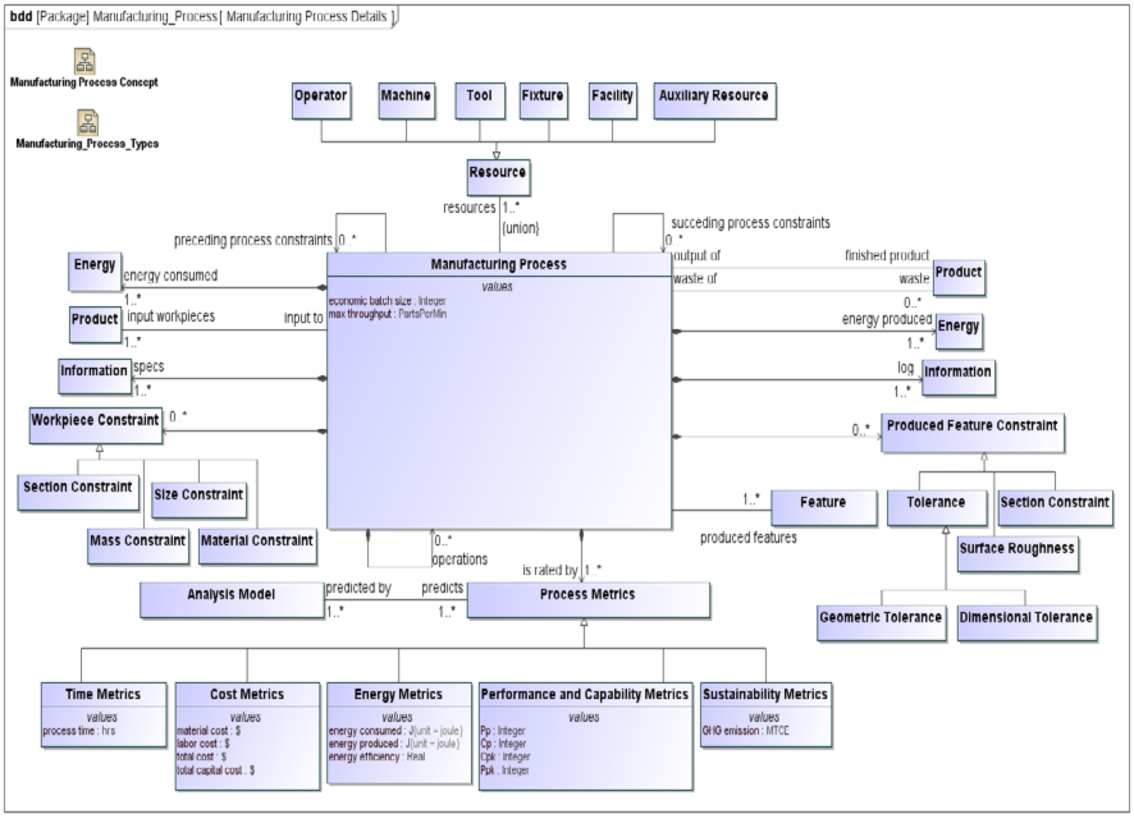


Figure 3.5: Manufacturing process concept – detailed view.

The SysML block definition diagram in Figure 3.5 illustrates a more detailed view of the manufacturing process concept. A manufacturing process has preceding process constraints and succeeding process constraints, representing processes that must be carried out before and after a given manufacturing process. Specific types of manufacturing processes (e.g. machining, welding, and additive manufacturing) may have workpiece constraints that bound the types of workpieces that the process can transform. Section constraints, size constraints, mass constraints, and material constraints are specific types of workpiece constraints used for bounding the range of workpieces that a process can transform. Similarly, specific types of manufacturing process may have product feature constraints that represent the range of features that the process of that type can produce. Tolerance, surface roughness, and section constraints are different types of product feature constraints used for bounding the range of product features that a process can produce. Both geometric and dimensional tolerances can be used. While geometric tolerances are specified on the overall shape of the feature (e.g. circularity of a hole), dimensional tolerances are specified on the characteristic dimensions of that shape (e.g. radius and depth of the hole).

A manufacturing process is rated by one or more process metrics. Time, Cost, Feasibility, Energy, Sustainability, and Capability are different classes of metrics that are used for rating and comparing manufacturing processes. There are one or more metrics in each class, such as energy consumed, energy produced, and energy efficiency are three specific energy metrics. Similarly, Cp / Cpk and Pp / Ppk are specific metrics for measuring process capability and performance respectively. New metrics can be added to existing or new classes. Process metrics are predicted using one or more analysis models of different fidelities.

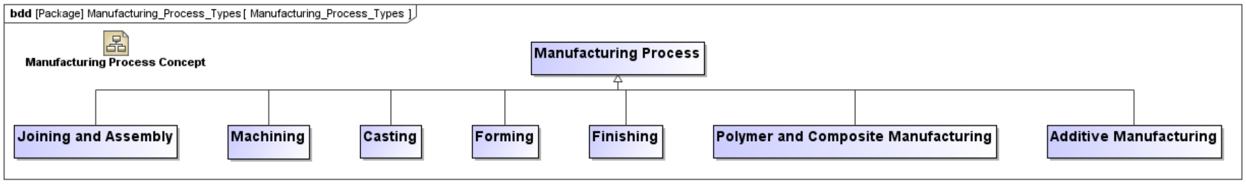


Figure 3.6: Manufacturing process classification – top-level view.

M-SysML provides an extensible approach for representing both conventional and non-conventional types of manufacturing processes. The SysML block definition diagram in Figure 3.6 illustrates the top-level classification of manufacturing processes. Each of these manufacturing process types is further elaborated. For example, Figure 3.7 illustrates a detailed classification of machining processes, Figure 3.8 illustrates a detailed classification of additive manufacturing processes, and Figure 3.9 illustrates a detailed classification of welding processes. See the M-SysML model in MagicDraw for the complete and detailed classification of manufacturing processes.

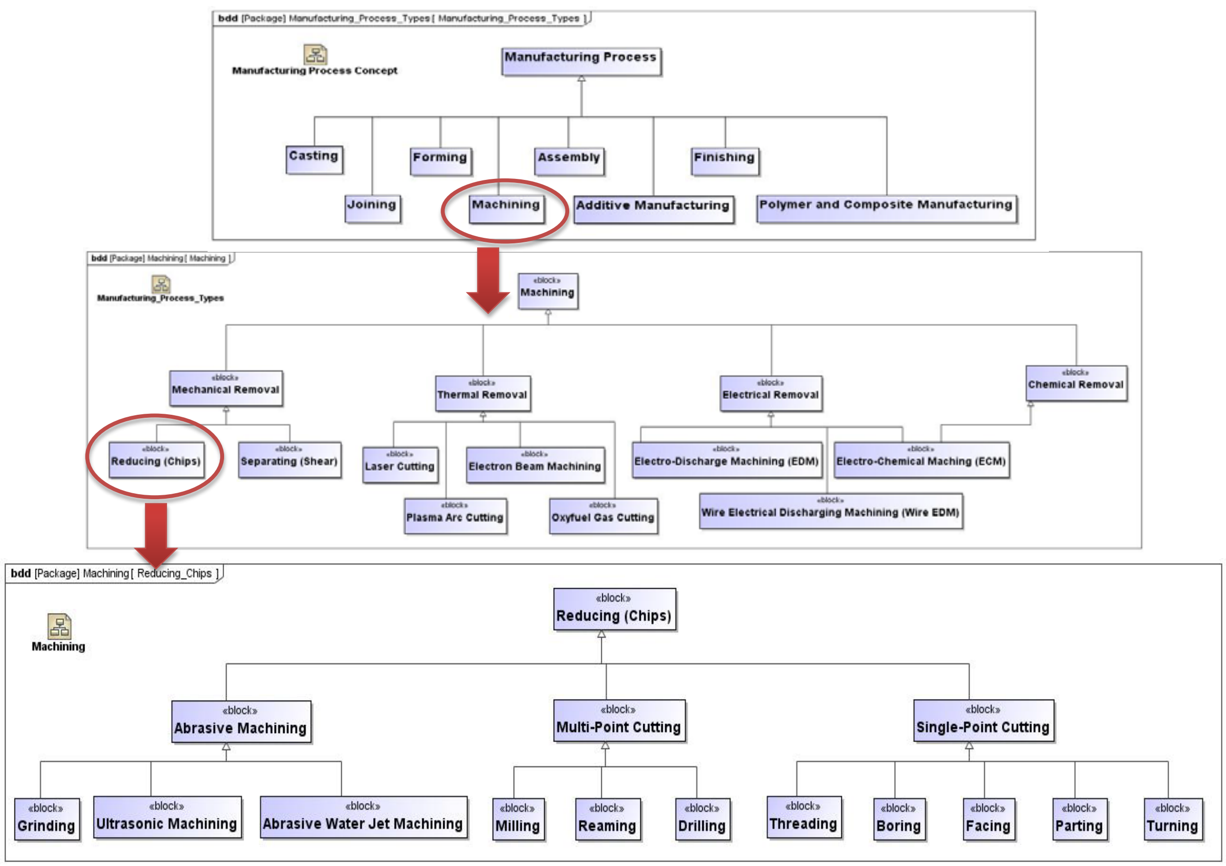


Figure 3.7: Detailed classification of machining processes.

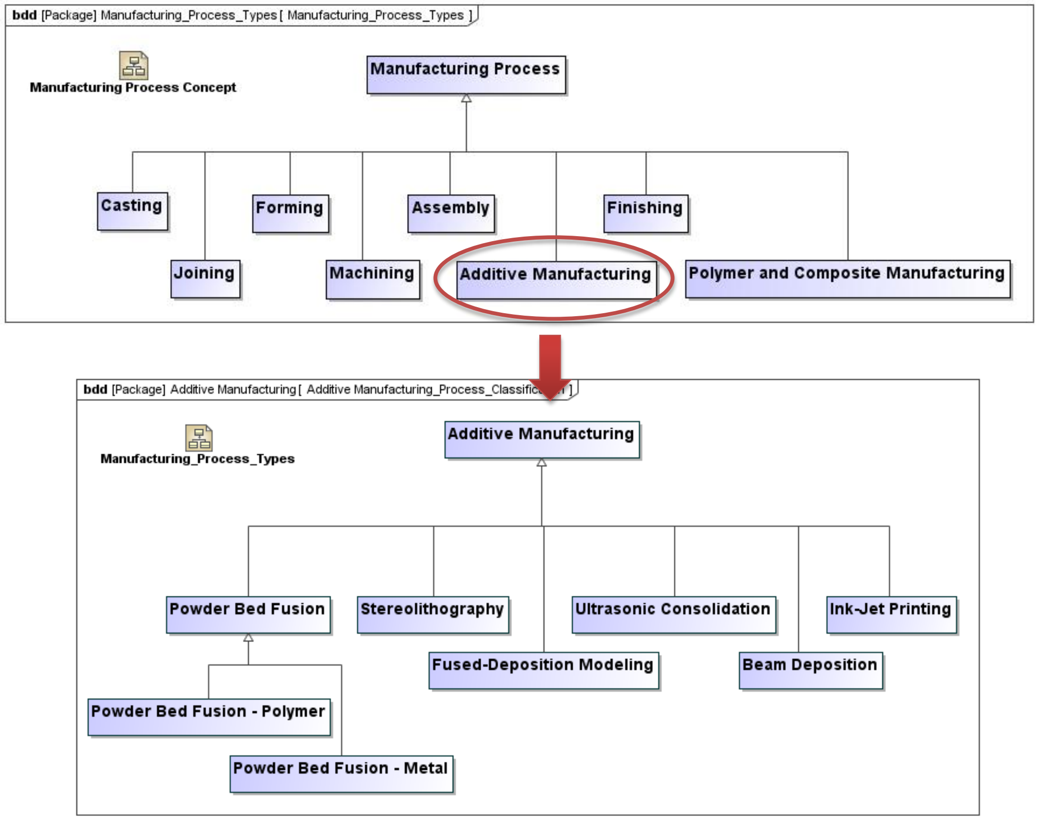


Figure 3.8: Detailed classification of additive manufacturing processes.

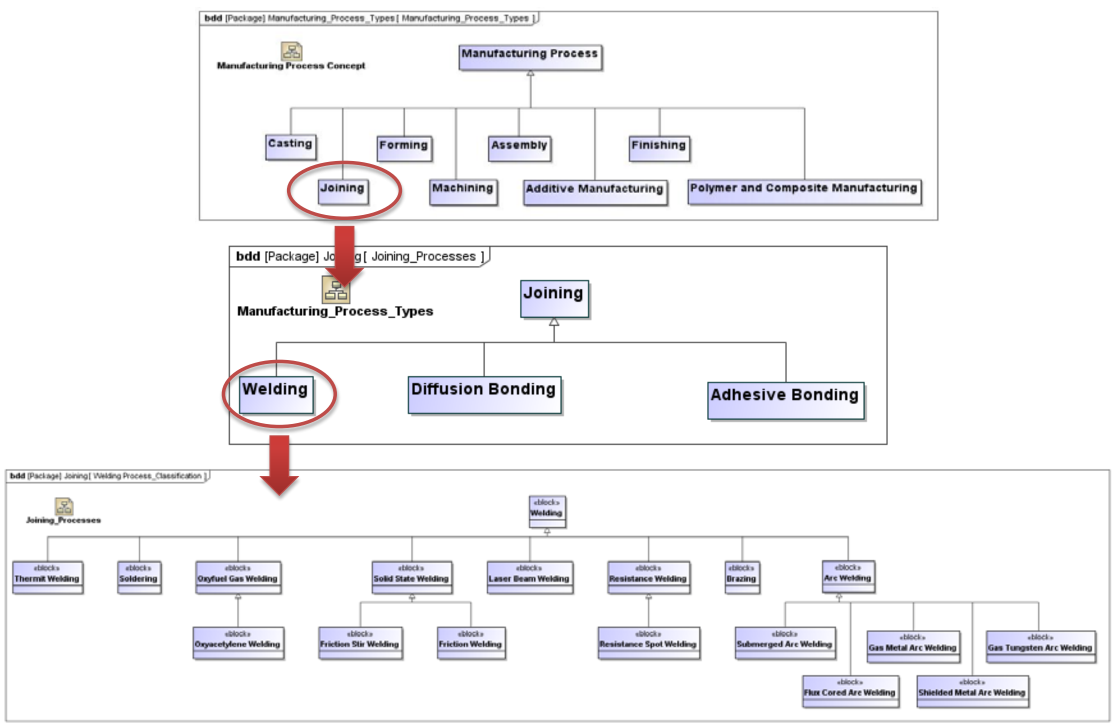


Figure 3.9: Detailed classification of welding processes.

In addition to a detailed classification of processes, the M-SysML knowledge graph also contains detailed characterization of individual processes. Figure 3.10 illustrates the detailed characterization of single-point cutting and multi-point cutting processes, both special types of machining processes. As an example, Figure 3.11 shows how the Drilling process is specialized. Drilling inherits all characteristics of a generic manufacturing process (Figure 3.5) through successive specialization (Figure 3.7). The inherited property *resources* is subsetted into machines, operators, fixtures, and auxiliary resources, each of which is typed by a specialization for drilling. This allows one to differentiate processes and the resources they use. For example, a Drilling process will use a Drilling Machine, and no other machine type. The Drilling Machine concept is specialized into different types of drilling machines, such as Radial Drill Press and CNC Drilling and Tapping Machine. The inherited property *resources* is a derived union, thus enforcing that resources for a specific process is a union of subsetted properties. For example, a drilling process will use only four types of resources, namely one or more drilling machines, machinists, drilling fixtures, and drilling aux resources. This constraint ensures that one may not add incompatible machines, tools, or fixtures as special resources for a drilling process (e.g. a fastening machine cannot be used for a drilling process).

Single-Point Cutting **Multi-Point Cutting**

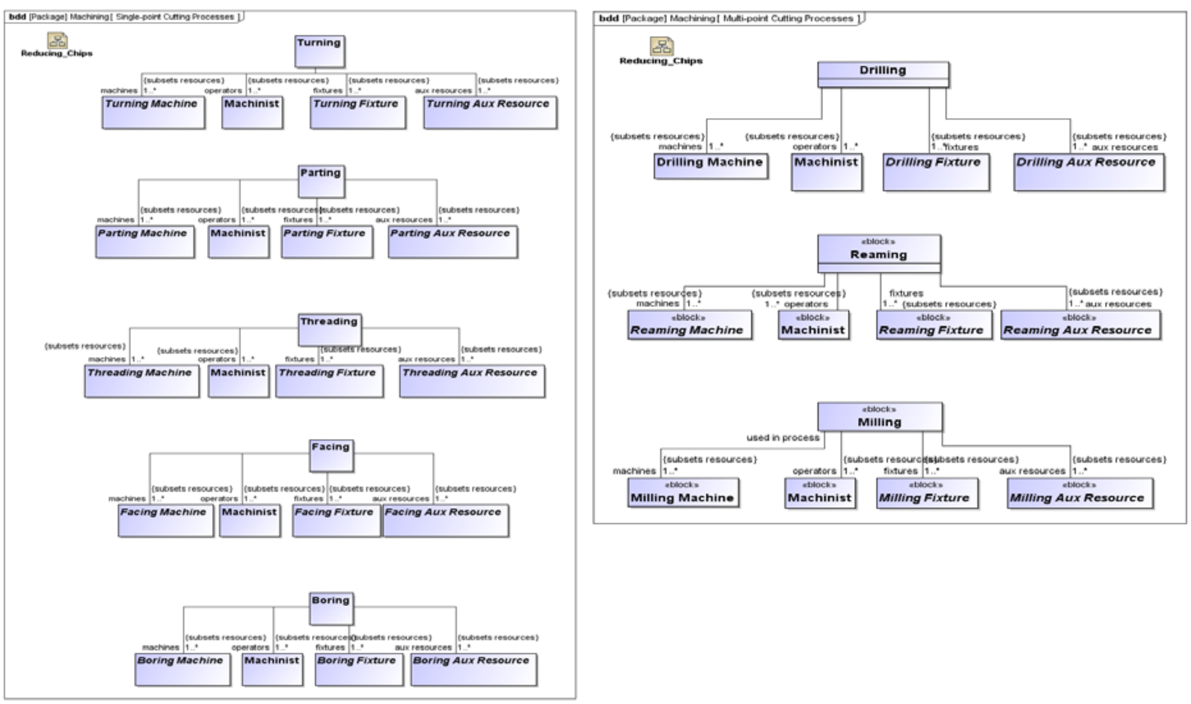


Figure 3.10: Characterization of manufacturing processes – single-point and multi-point cutting processes.

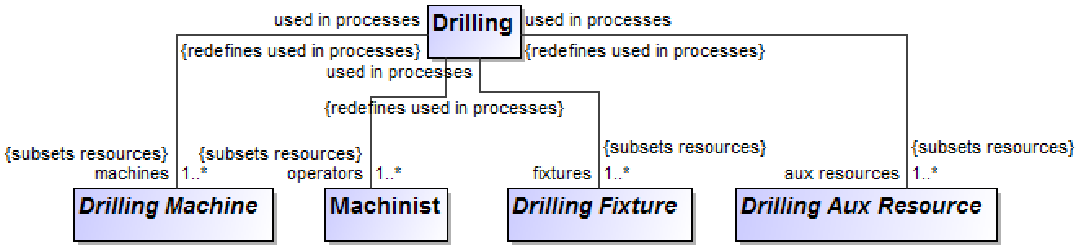


Figure 3.11: Characterization of manufacturing processes – drilling process as an example.

Product concept

A manufacturing process transforms workpieces (including raw material) to finished products. The product concept in M-SysML is used to represent raw materials, finished products, any interim products (workpieces), and the fasteners that are typically purchased off-the-shelf for mechanical fastening (assembly process). Figure 3.12 is a SysML BDD illustrating the specialization of product concept.

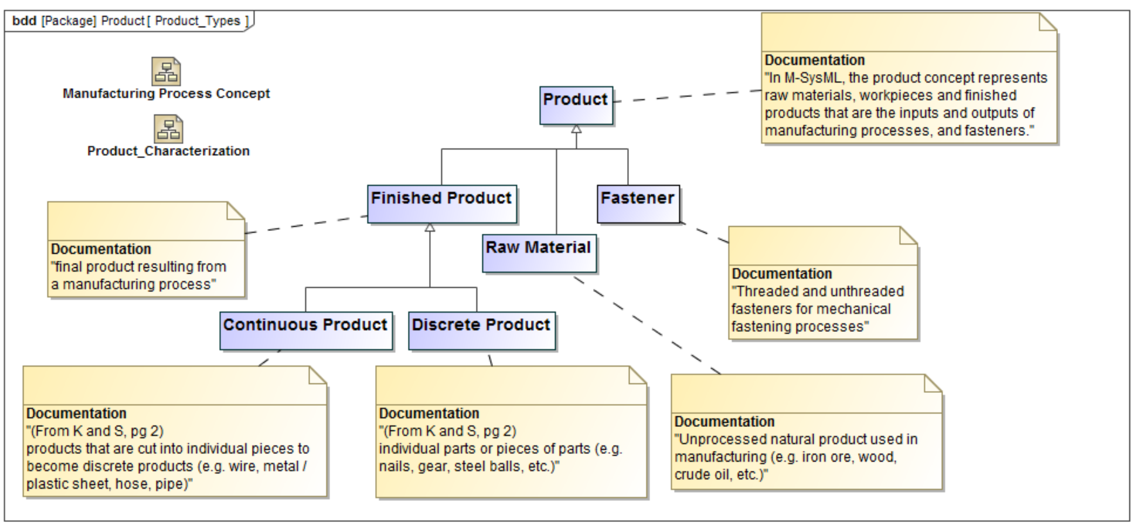


Figure 3.12: Product concept in M-SysML – specialization view.

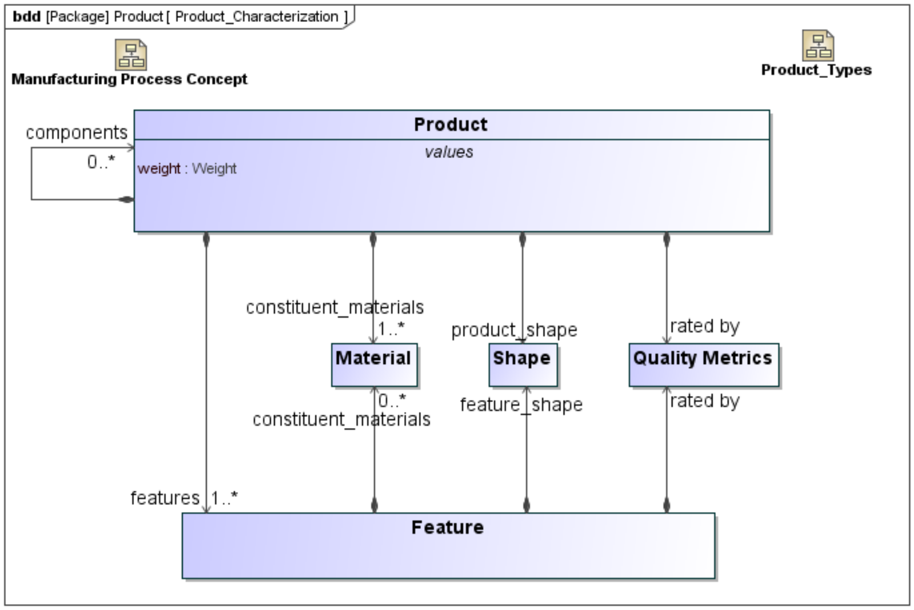


Figure 3.13: Product concept – characterization view.

Figure 3.13 is a SysML BDD illustrating the characterization of the product concept. A product may be a single piece part or an assembly (of multiple parts/assemblies). A product has shape and is constituted of one or more materials. A product has one or more features, and each feature has a shape and may be constituted by a material—material removal features like holes do not have a constituent material. Products and their features are rated by quality metrics, such as surface finish for finished products.

M-SysML provides a detailed feature classification system to describe process capabilities. Figure 3.14 and Figure 3.15 illustrate the feature classification system.

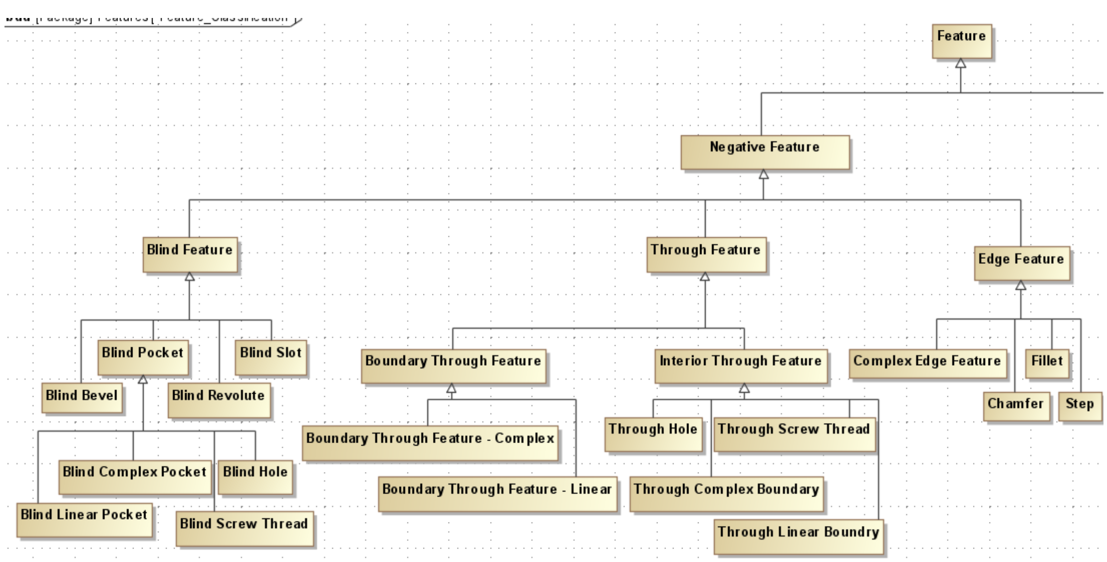


Figure 3.14: Feature classification – Negative features.

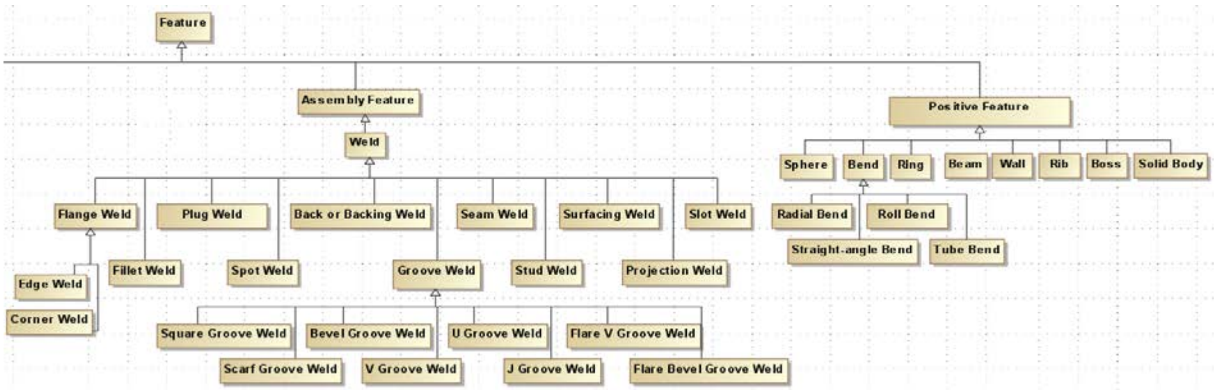


Figure 3.15: Feature classification – Positive and Assembly features.

Material concept

In M-SysML, the material concept is specialized into different types of materials, such as Metal, Alloy, Ceramic, Composite, Glass, and Plastic. Figure 3.16 is a SysML BDD illustrating the specialization of the Material concept.

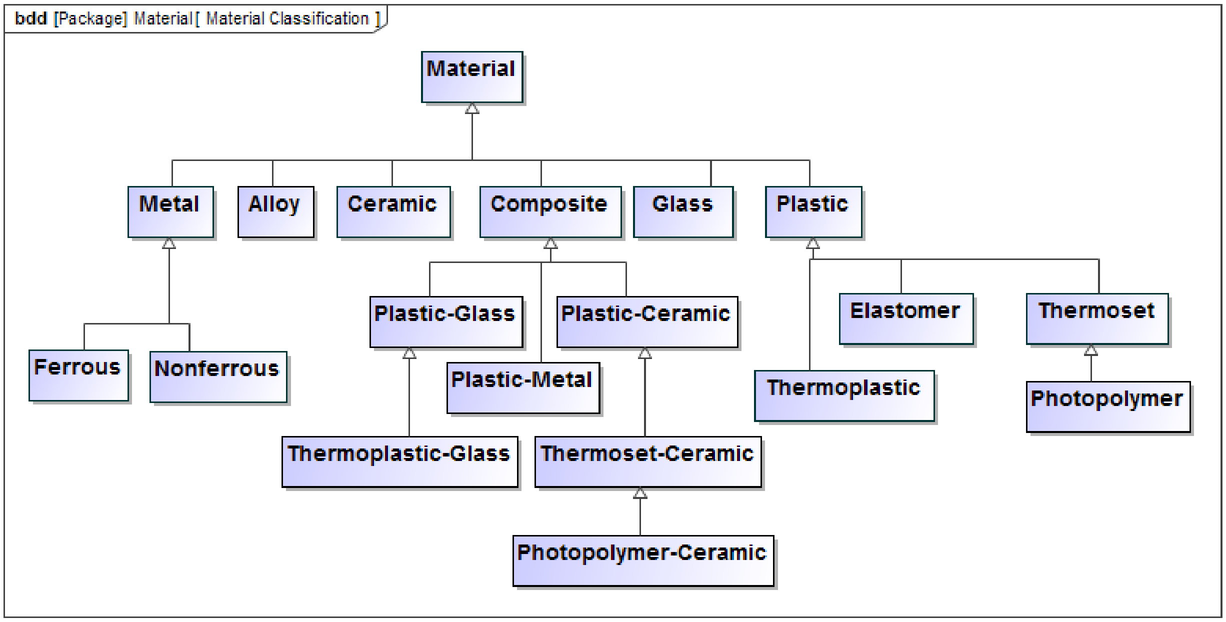


Figure 3.16: Material classification.

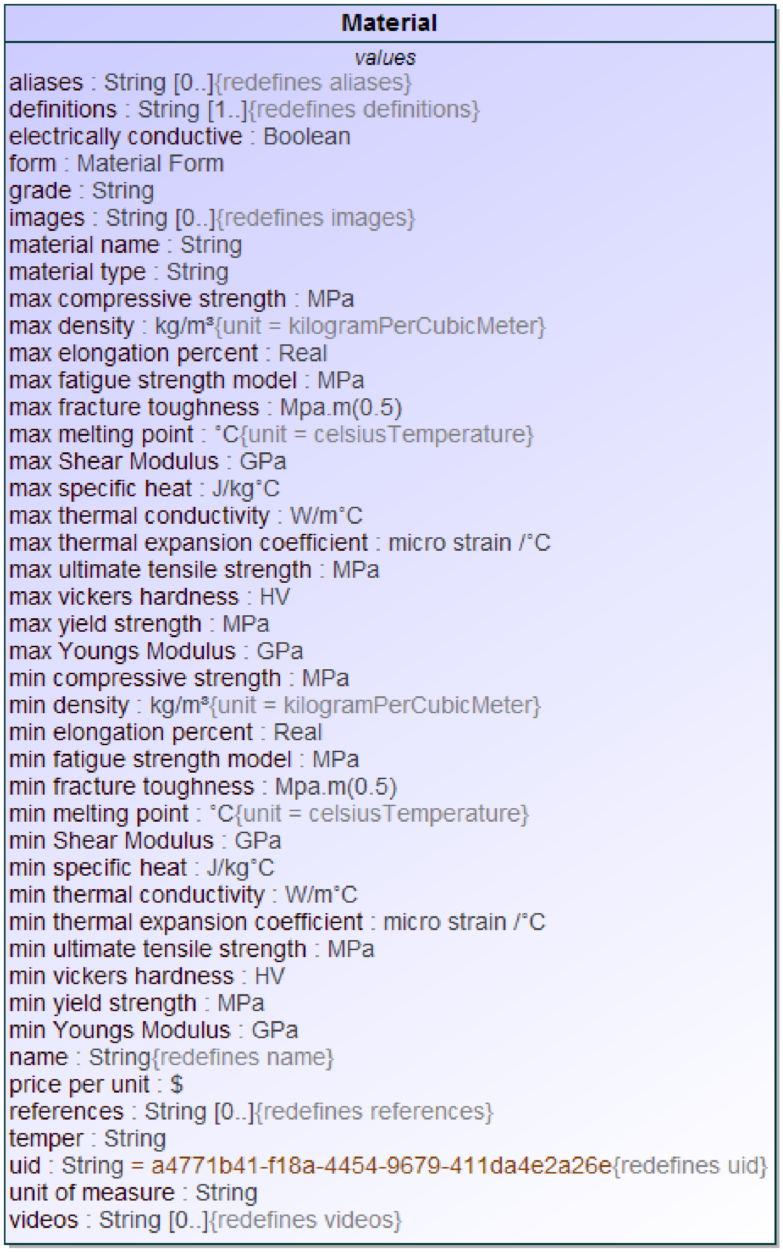


Figure 3.17: Material concept – detailed attributes.

The Material concept is characterized by properties shown in Figure 3.17 above. The M-Library contains 314 material instances, including all different types of materials shown in Figure 3.16.

Operator concept

Figure 3.18 is a SysML BDD fragment illustrating the operator concept. In M-SysML, the operator concept represents humans that set-up, control, monitor, and maintain manufacturing processes and machines. Every operator has an hourly rate and a set of skills that are typically matched against a machine's / process' operational requirements before operators are assigned to them. An operator can operate one or more machines, and a machine can be operated by one or more operators. The relationship between the operator concept and the machine concept in Figure 3.18 is used to allocate specific operators to specific machines in a manufacturing process. Different types of operators are identified for different processes, as shown in Figure 3.18.

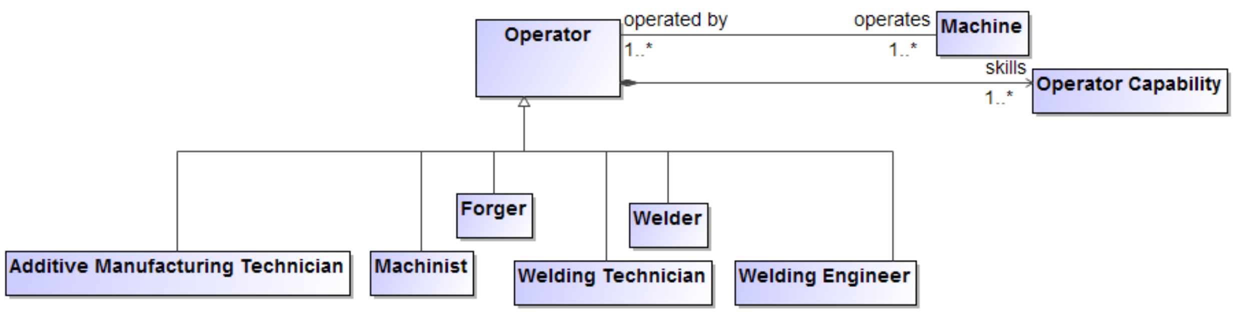


Figure 3.18: Operator concept.

Machine and Tool concepts

In this section, the machine and machine tool concepts in M-SysML are presented. Figure 3.19 is a SysML BDD diagram illustrating the high-level machine-tool relationship in M-SysML. The Machine concept represents manufacturing machines, including robots, and is characterized by a set of properties, such as dimensions, ports, existence of CNC controllers, etc. A machine is operated by one or more operators, and has one more tools installed. The tool concept represents all machine tools, such as cutting tools and laser tools. A tool can be installed on any compatible machine. Similar to a machine, a tool has a list of properties, such as degrees of freedom, max speed, min speed, tool dimensions, positioning accuracy, and resolution. The choice of tool(s) used with a machine depends on the type of process being performed using the machine, the type of workpiece, and the desired levels of performance and product / feature quality.

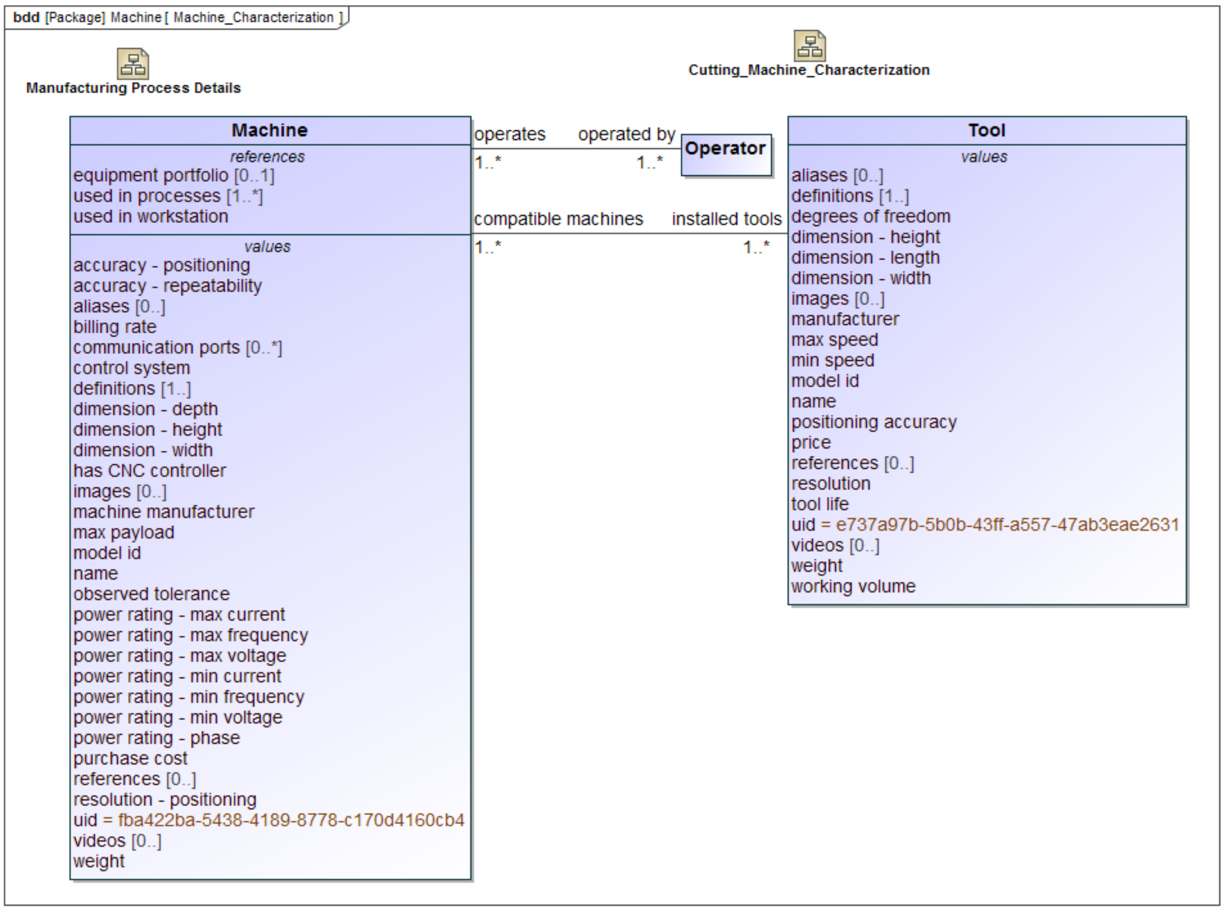


Figure 3.19: Machine and Tool concept in M-SysML.

Similar to manufacturing processes, M-SysML has a detailed classification of machines, as shown in Figure 3.20 below. The figure also illustrates further classification of Welding machines as an example. Refer to the M-SysML model in MagicDraw for detailed classification of different machine types. There are 184 types of machines defined in M-SysML, including all abstractions. Each machine type, such as CNC Drilling and Tapping Machine, is instantiated in the M-Library. Each instance represents a specific machine with a serial number that would be deployed in the iFAB foundry. There are 524 machine instances in the M-Library.

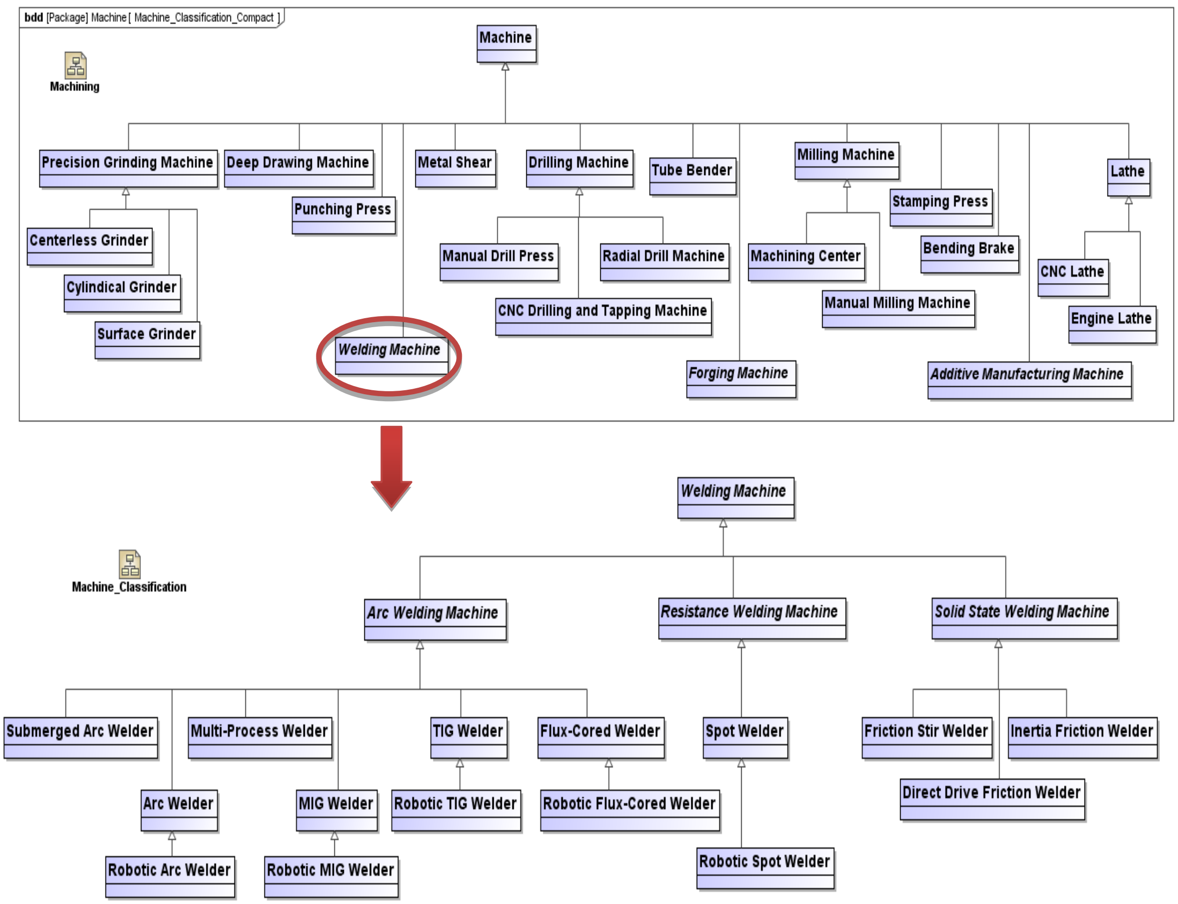


Figure 3.20: Machine classification illustrating detailed specialization for welding machines.

The M-SysML model also contains detailed characterization of machines, as shown in the SysML BDD in Figure 3.21 below. The attributes of *CNC Drilling and Tapping Machine* are zoomed in as an example. Refer to the M-SysML model in MagicDraw for the characterization of all machine types.

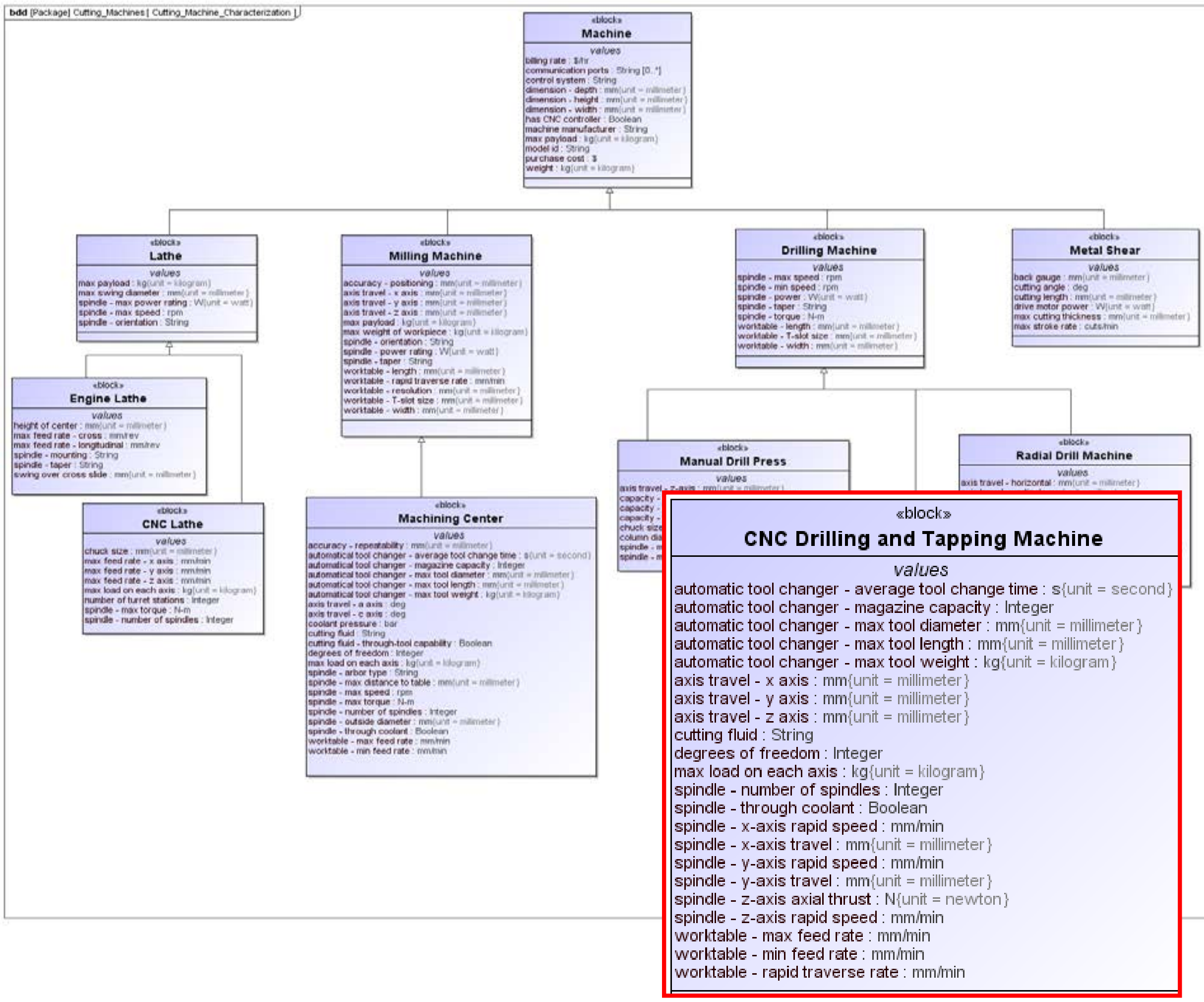


Figure 3.21: Machine characterization.

Figure 3.22 illustrates a top-level view of tool classification in M-SysML. Tool concepts illustrated in the figure are further classified, as shown for fastening tools in Figure 3.23 below. Similarly, there exists a detailed classification of welding tools and forging tools.

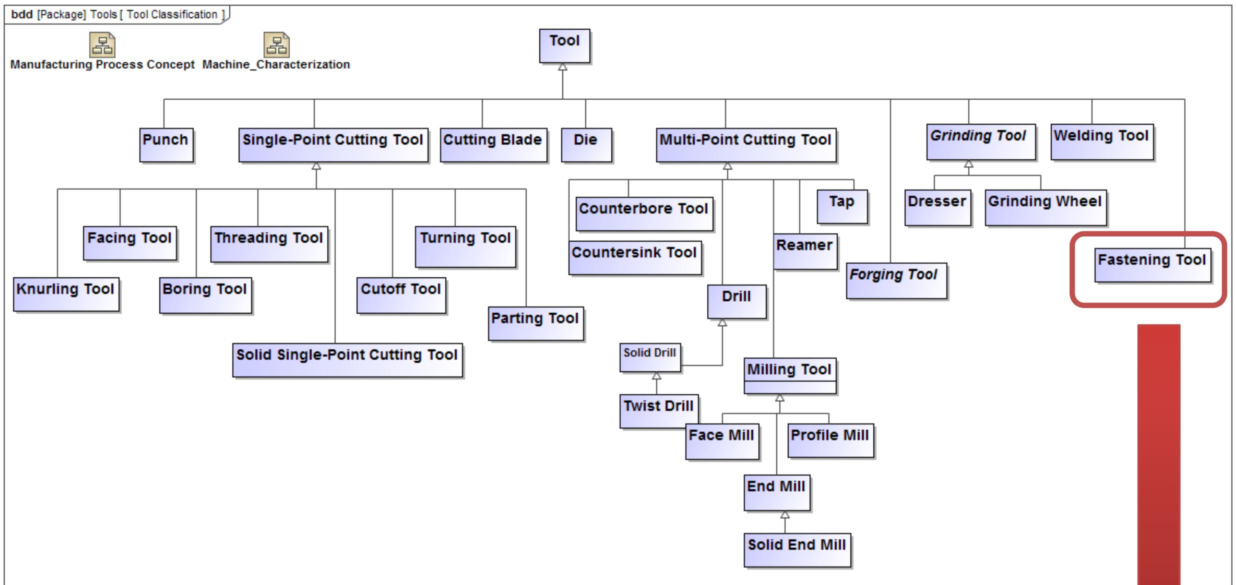


Figure 3.22: Tool classification – top-level view.

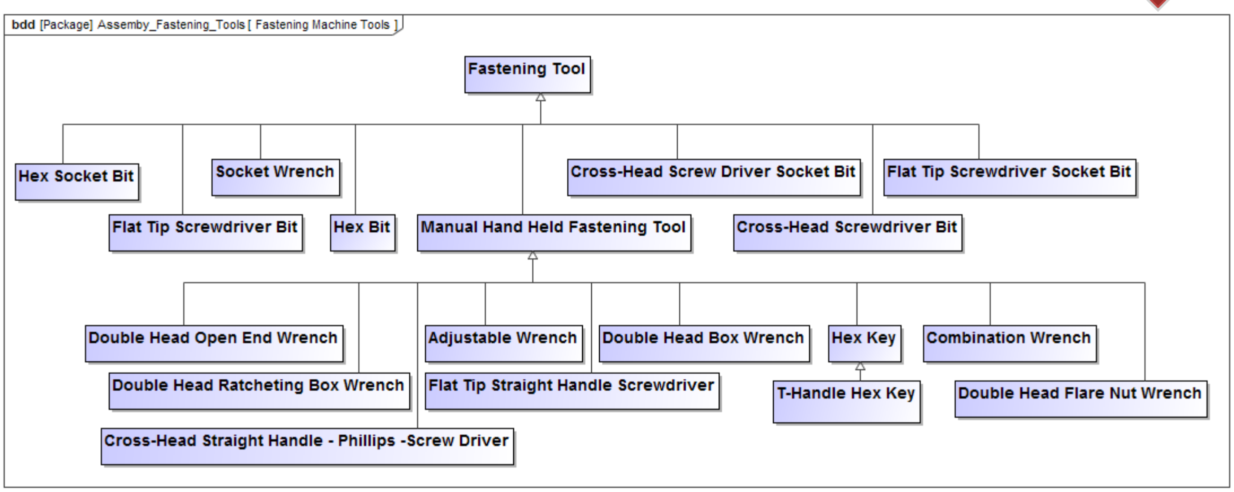


Figure 3.23: Fastening tool classification.

Fixture concept

In M-SysML, a fixture is a device that is used to locate, clamp, and support a workpiece during a manufacturing process. Figure 3.24 below illustrates fixture classification in M-SysML. The detailed characterization of each fixture type is not shown in the figure.

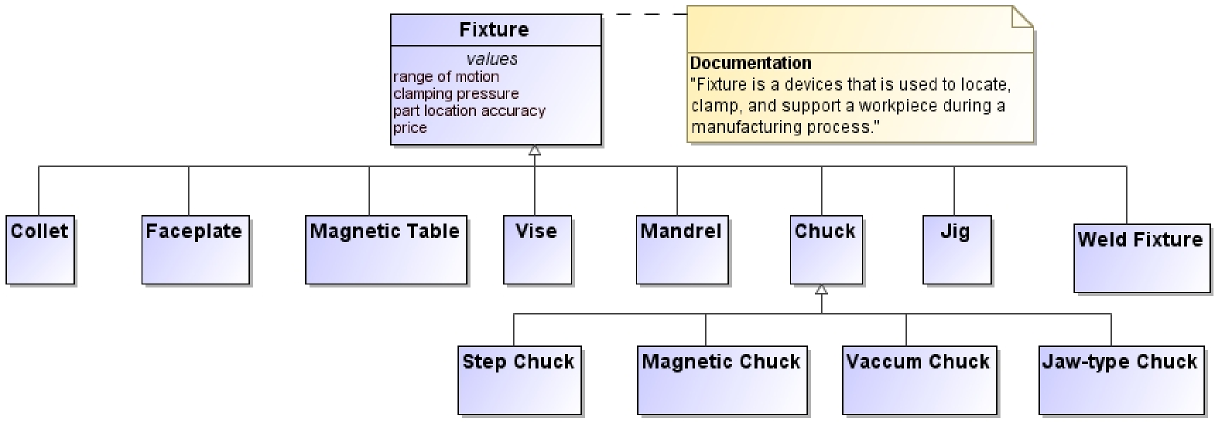


Figure 3.24: Fixture classification.

Facility concept

The facility model in M-SysML allows the representation of both logical and physical foundries. Logical foundry—represented by *Facility* concept in Figure 3.25—provides information on the functional components of the foundry, such as departments, workstations, movement channels, and the overall equipment portfolio. In contrast, the physical foundry—represented by *Layout for Movement and Access* concept in Figure 3.26—provides information on candidate physical layouts of a logical foundry. Figure 3.28 illustrates the relationships between logical and physical foundries.

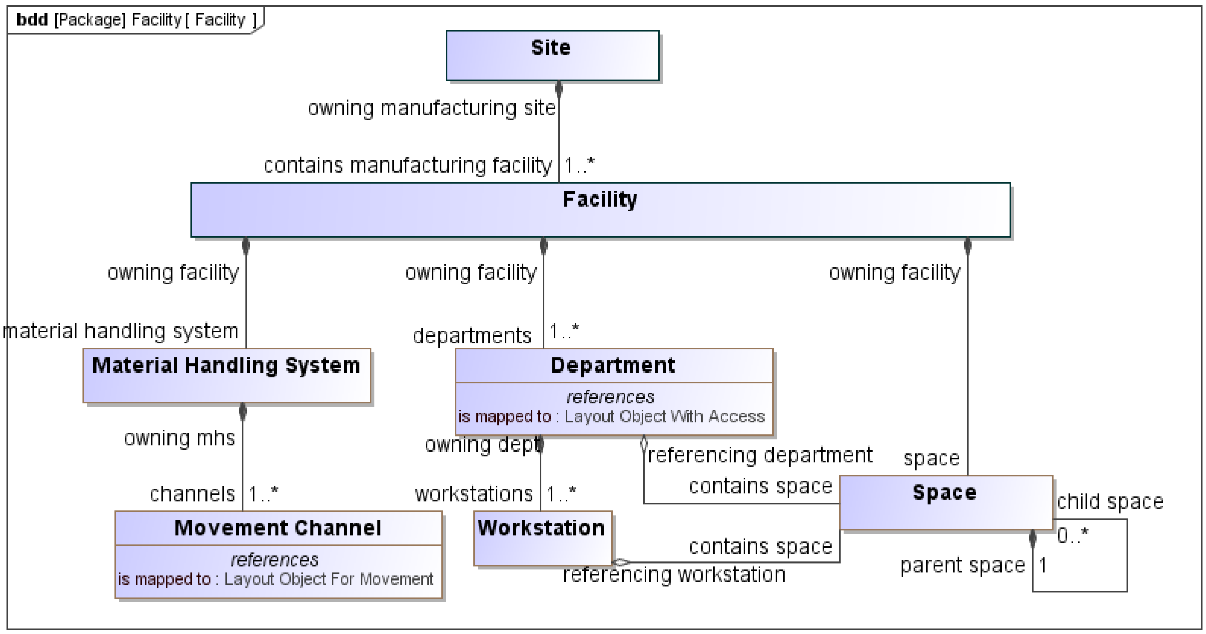


Figure 3.25: Facility concept.

A manufacturing site contains one or more manufacturing facilities, with a facility understood as a single building. A manufacturing facility is organized by departments, and departments organized by workstations. Material movement among departments and workstations is enabled by a Material Handling System. Note that semantics are chosen to allow functional design, which can later be refined into a physical implementation (hence an abstract 'Movement Channel' first and later an 'Aisle' - the latter is an implementation of the former).

The relationships between a manufacturing facility and the resources contained within are important. Questions such as "Given this facility and this process plan, can I make a certain part?" require traceability from a facility to the machines within to the capabilities of each machine. Questions concerning a facility's capacity require traceability to the equipment contained in the facility. Figure 3.26 shows the relationships.

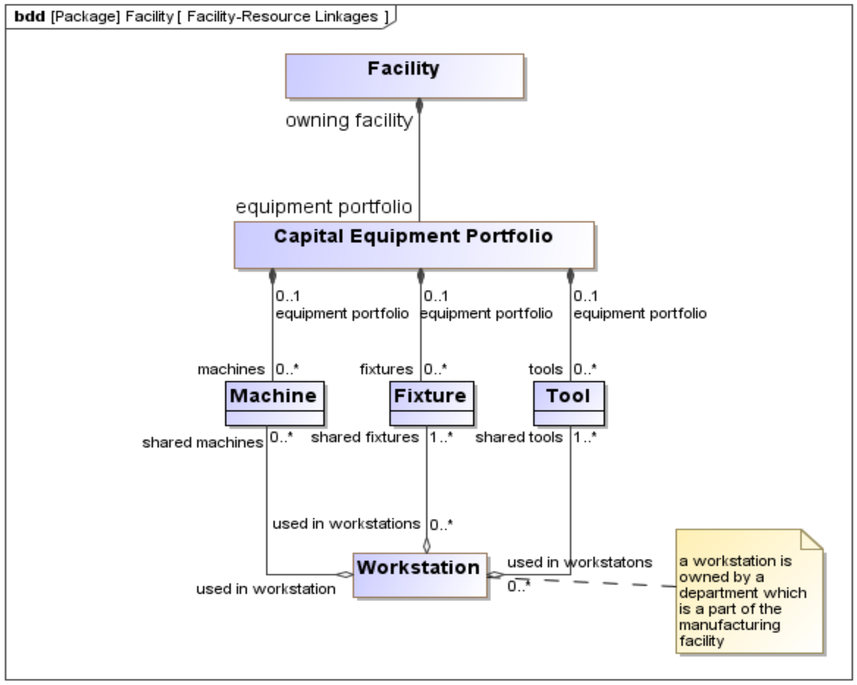


Figure 3.26: Every manufacturing facility has an equipment portfolio that provides information on machines, tools, fixtures, and other resources at that facility.

Any facility has a layout, as does each department and each workstation (Figure 3.27). A layout is a set of placements, and placement involves offsetting and orienting objects such as machine workstations, aisles, and conveyors within available space. Given a layout and a specific process plan (with resource assignments), this enables evaluating material movement performance metrics.

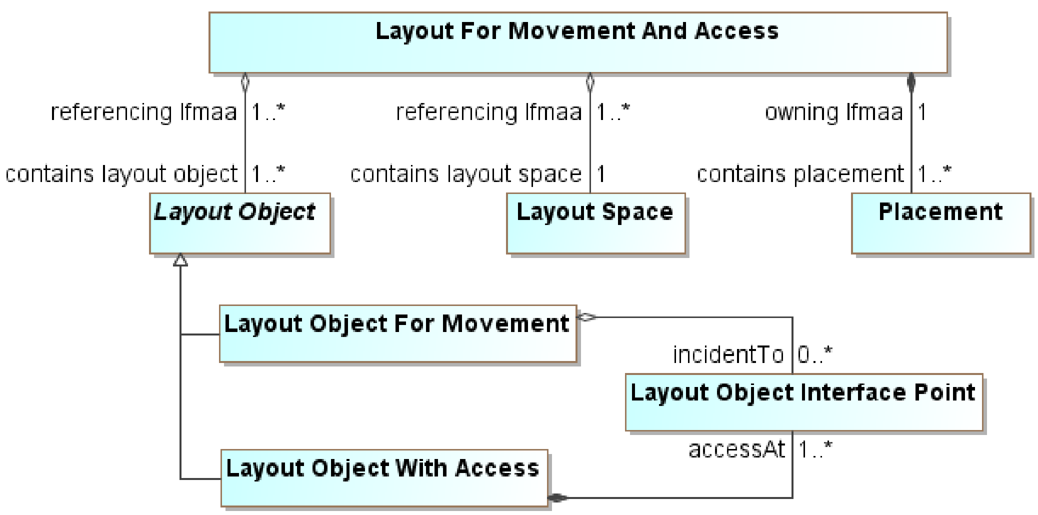


Figure 3.27: Foundry layout model in M-SysML.

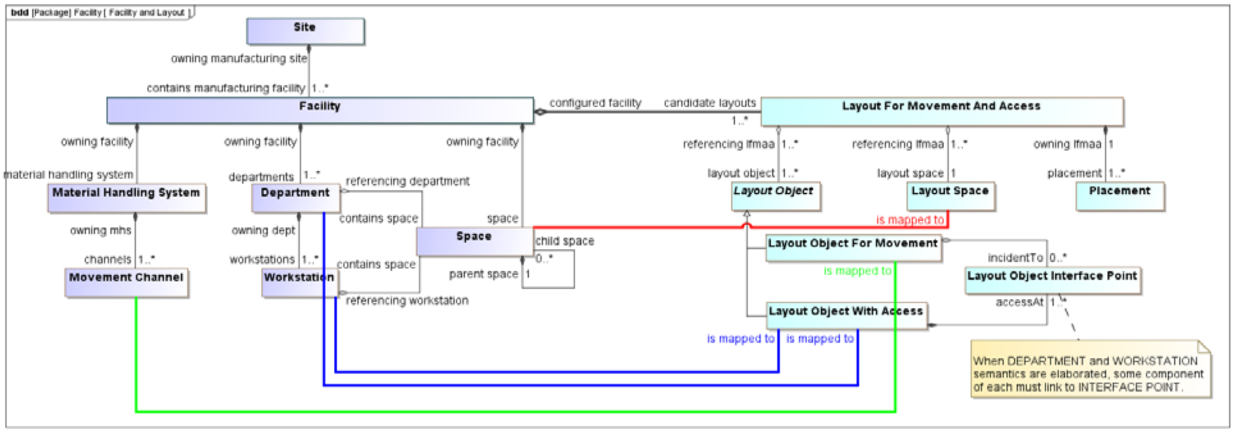


Figure 3.28: M-SysML enables representation of logical foundries, physical foundries, and their inter-relationships.

4.3.2 M-Library Web Dashboard

The M-Library Web Dashboard is a web application for browsing, querying, populating, and updating M-Libraries. The dashboard can be used to browse and query both M-SysML concepts and specific instances of each concept.

Figure 3.29 illustrates a view of the dashboard for Drilling process. The left hand side (LHS) tree is the concept type hierarchy. It lists every major concept type (e.g. Manufacturing Process, Product, and Machine) in M-SysML and their successive specializations. When a specific concept is selected in the LHS tree, the dashboard shows details about that concept and instances of that concept in the M-Library database. As shown in Figure 3.29, users can see definition, attributes, and other illustrations of the concept. The model content displayed in the dashboard is auto-generated from the M-SysML model. The concept instances reside in an object oriented database that is connected to the dashboard.

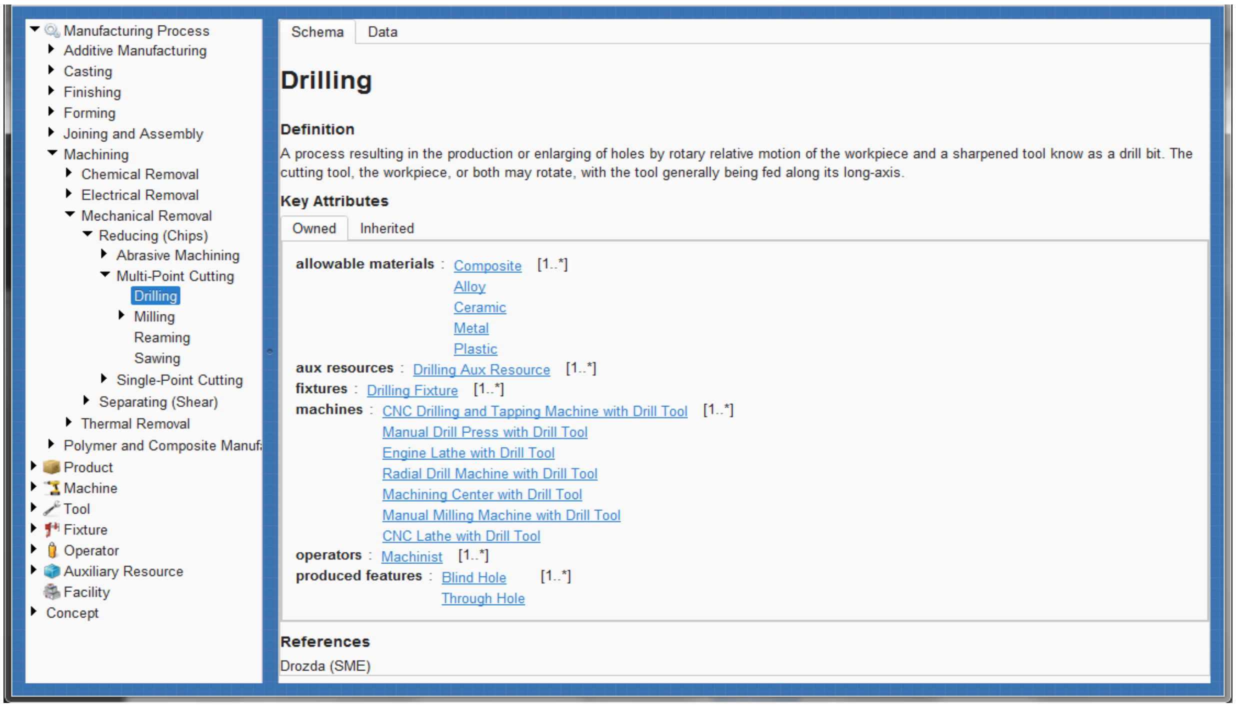


Figure 3.29: M-Library Web Dashboard – view of Drilling process concept.

If a concept has instances in the databases, the dashboard presents those instances in a table on the concept page under the Data tab on the top (Figure 3.30). Users can turn off/on variables (columns) displayed in the table. Additionally, users can generate charts to visualize instances, as demonstrated by the scatter plot of machine height versus weight attribute in Figure 3.30.

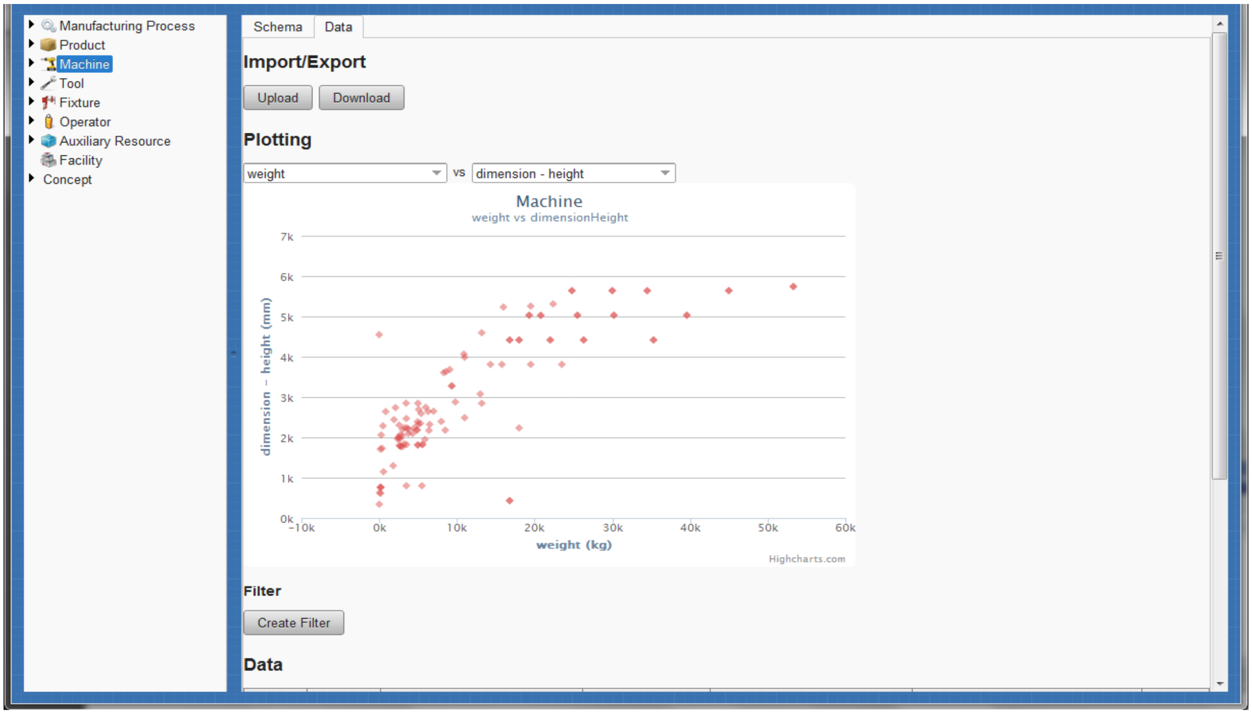


Figure 3.30: Dashboard view for Machine concept showing machine instances and auto-generated scatter plot from the instance table.

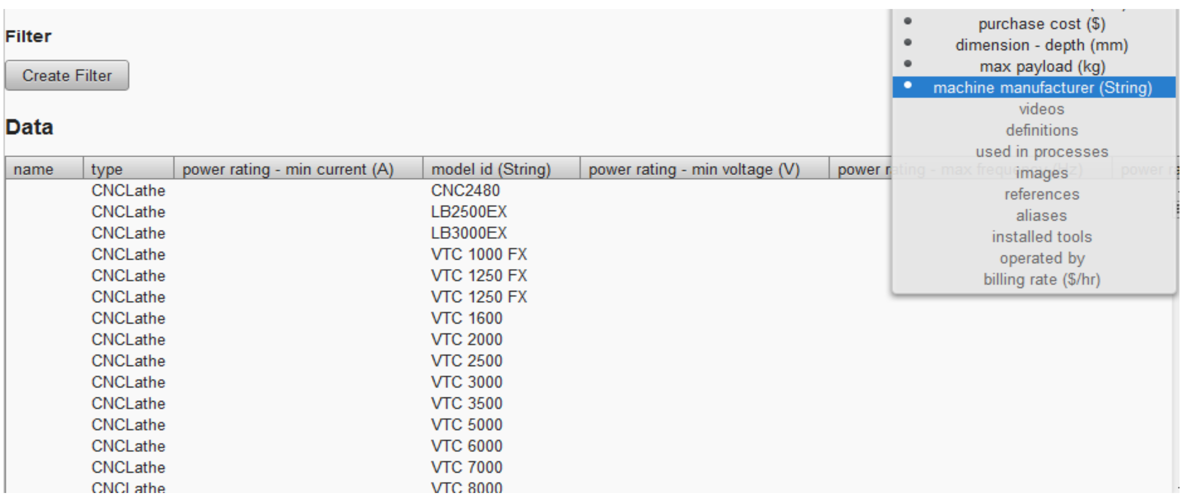


Figure 3.31: Dashboard view showing table with instances of CNC Lathe machine.

A key capability of the dashboard is a simple-to-use query interface. Users can easily formulate queries for any concept (based on the properties) and execute those queries on the M-SysML *concept model* or *instances* in the M-Library database.

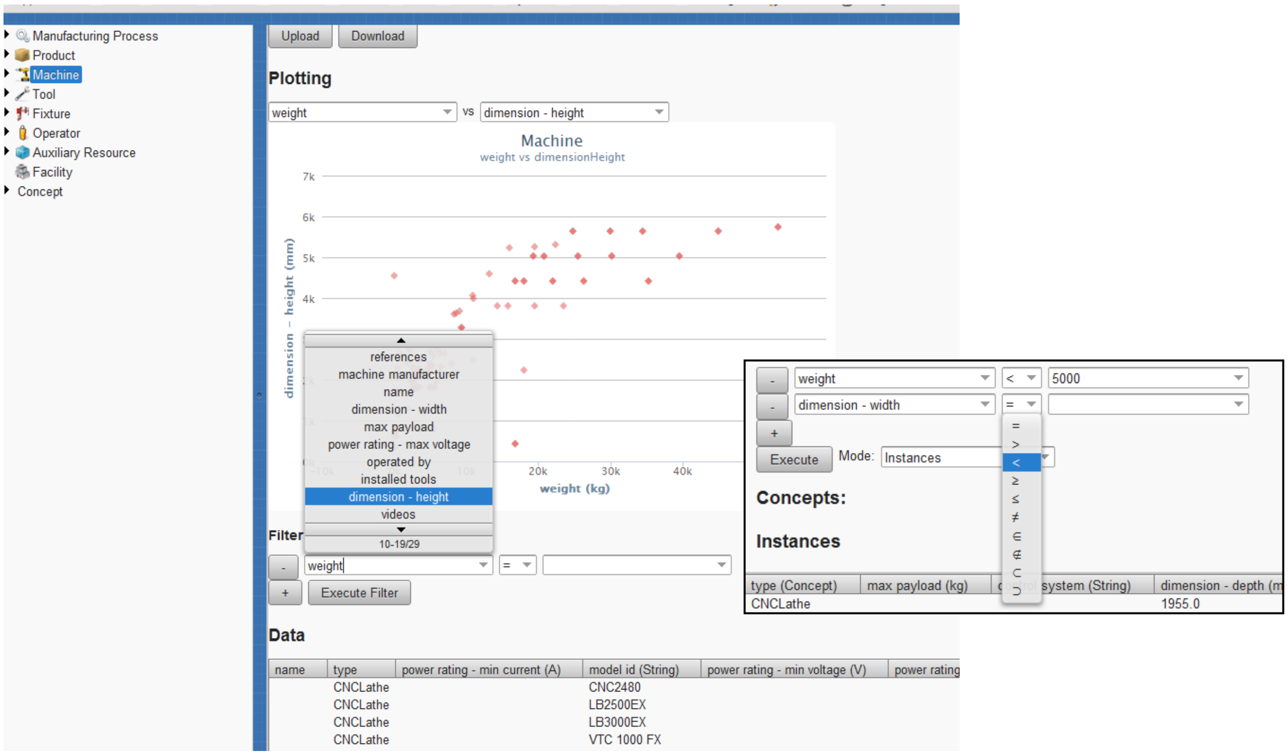


Figure 3.32: Users can define filters to select instances based on one or more criteria.

A query/filter is composed of one or more criteria defined using concept properties. A range of math operators are available, such as <. >, =, and set-based operators (subset of, element of). When queries are executed on instances, the result (filtered set of instances) is shown in the instance table (Figure 3.32) and any corresponding charts are updated. Queries can also be formulated and executed on the concept meta-model, such as find all manufacturing processes that can produce a Straight-angle Bend (Figure 3.33), the dashboard returns a list of concepts (e.g. processes) that match the criteria.

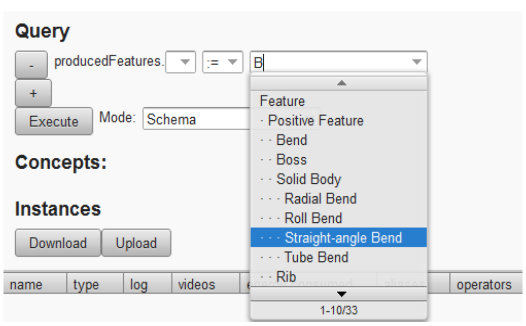


Figure 3.33: Queries can be executed on the M-SysML concept model schema, e.g. to search for all processes that can produce a specific type of feature on a given type of material.

The dashboard also provides end users the capability to download instances of any concept as Excel spreadsheets. Alternatively, users can update the library by uploading spreadsheets conforming to the library templates. Figure 3.34 below shows the Machine instance spreadsheet downloaded from the dashboard.

A	B	C	F	G	H	I	J	K	L
Type	Machine								
Attributes	Object ID	Subtype	dimension - depth	dimension - height	dimension - width	has CNC controller	machine manufacturer	max payload	model id
Units			mm	mm	mm	Boolean	String	kg	String
	4F05EF6A DCC360C6 600155E1	CNCLathe	1719.6	1821.2	4980.9		clausing		CNC2480
	4F05EF6A DCC360C6 600155EA	CNCLathe	1640	1770	1734		okuma		LB2500EX
	4F05EF6A DCC360C6 600155EB	CNCLathe	1895	1950	3310		okuma		LB3000EX
	4F05EF6A DCC360C6 600155EC	CNCLathe				yes	mag		VTC 1000 FX
	4F05EF6A DCC360C6 600155ED	CNCLathe				yes	mag		VTC 1250 FX
	4F05EF6A DCC360C6 600155EE	CNCLathe				yes	mag		VTC 1250 FX
	4F05EF6A DCC360C6 600155EF	CNCLathe				yes	mag		VTC 1600
	4F05EF6A DCC360C6 600155F0	CNCLathe				yes	mag		VTC 2000
	4F05EF6A DCC360C6 600155F1	CNCLathe				yes	mag		VTC 2500
	4F05EF6A DCC360C6 600155F2	CNCLathe				yes	mag		VTC 3000
	4F05EF6A DCC360C6 600155F3	CNCLathe				yes	mag		VTC 3500
	4F05EF6A DCC360C6 600155F4	CNCLathe				yes	mag		VTC 5000
	4F05EF6A DCC360C6 600155F5	CNCLathe				yes	mag		VTC 6000
	4F05EF6A DCC360C6 600155F6	CNCLathe				yes	mag		VTC 7000
	4F05EF6A DCC360C6 600155F7	CNCLathe				yes	mag		VTC 8000
	4F05EF6A DCC360C6 60015602	MachiningCenter				yes	mori seiki		NVX7000 / 50
	4F05EF6A DCC360C6 60015603	MachiningCenter				yes	mori seiki		NH4000 DCG
	4F05EF6A DCC360C6 60015604	MachiningCenter				yes	mori seiki		NH5000 DCG / 40
	4F05EF6A DCC360C6 60015605	MachiningCenter				yes	mori seiki		NH5000 DCG / 50
	4F05EF6A DCC360C6 60015621	CNCDrillingAndTappingMachine		800		yes	Gentec		MH-206
	4F05EF6A DCC360C6 60015624	ManualDrillPress	990.6	1727.2	635		Jet	50	JDP-20VS-3/230 VAR/S
	4F05EF6A DCC360C6 60015626	ManualDrillPress	800	2285	470		Clausing		B35
	4F05EF6A DCC360C6 60015627	ManualDrillPress	910	2640	590		Clausing		B70
	4F05EF6A DCC360C6 60015601	MachiningCenter				yes	mori seiki		NVX7000 / 40
	4F05EF6A DCC360C6 60015615	BendingBrake	2743	4547	1905	yes	US Industrial		USHB250 - 13

Figure 3.34: Machine instance spreadsheet downloaded from the dashboard.

Refer to Appendix 3A for details on the types of queries that can be formulated and executed for M-Library.

M-Library Java API

MACME also provides a Java application programming interface (API) to programmatically interact with the M-Library. Teams developing process planning algorithms in the iFAB program need to invoke M-Library services in their algorithms. The Java API makes this possible. Figure 3.35 shows the scala/java doc for the M-Library Java API. The API enables access to both the M-SysML knowledge graph as well as the instance database. The M-Library web dashboard application also uses this Java API at the backend.

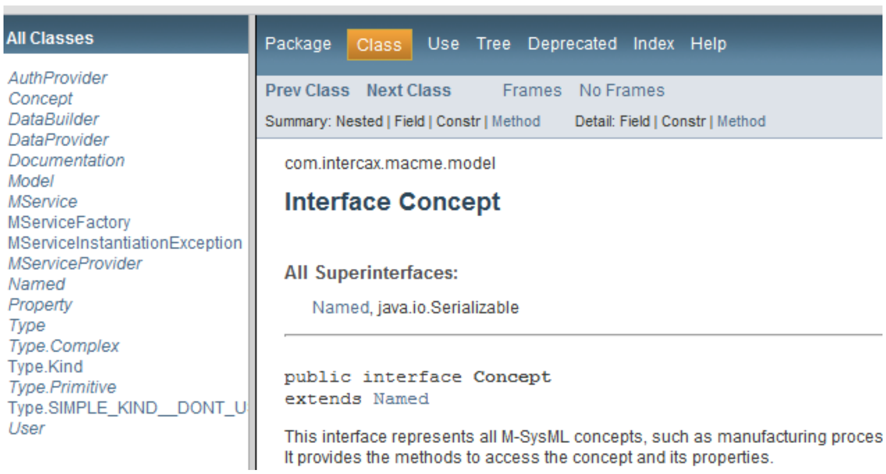


Figure 3.35: Java API to programmatically interact with M-Library.

4.3.3 M-Library Validation

The M-Library has been validated using the following three challenge problems.

1. GTRI Blast-Resistant Crew Cabin
2. iFAB Assembly Challenge Problem 1 (Jan 2012 PI Meeting, Camp Pendleton)
3. iFAB Assembly Challenge Problem 2 (Mar 2012 PI Meeting, Purdue University)

In this section, the use of the M-Library for these three challenge problems is presented.

GTRI Blast-Resistant Crew Cabin (ULTRA-II)

The ULTRA-II — GTRI's Blast-Resistant Crew Cabin assembly is shown in Figure 3.36.

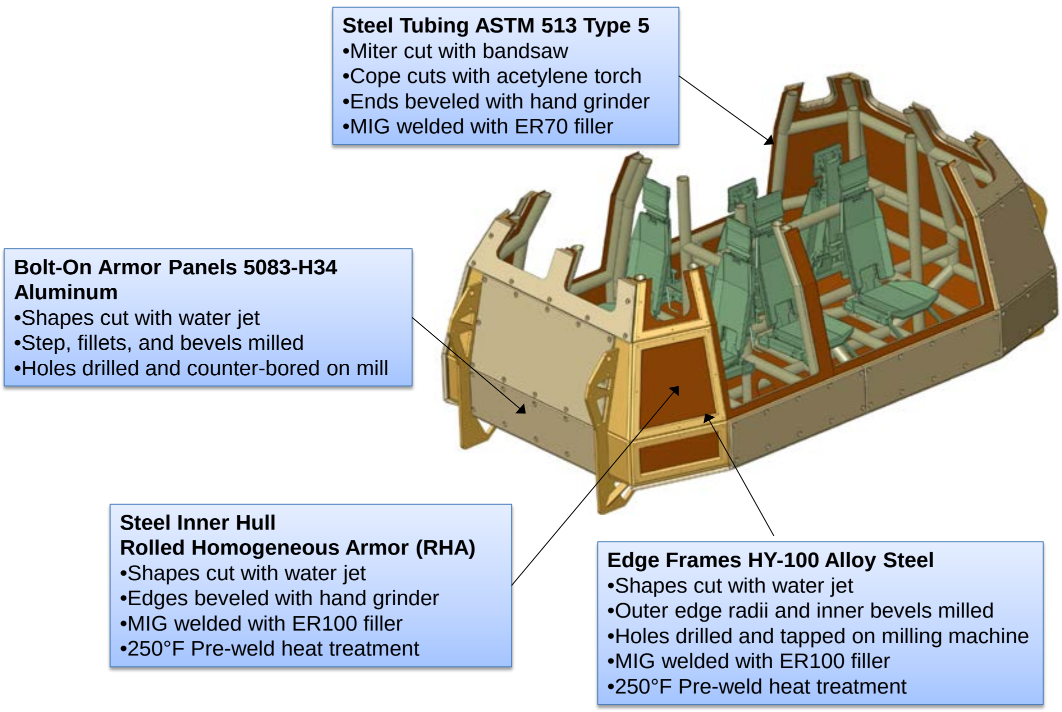


Figure 3.36: GTRI's blast-resistant crew cabin.

A specific part, ULTRA-9007, was selected as a challenge problem for exercising the M-Library. Figure 3.37 shows the specific part with annotations identifying features (as defined in the M-SysML feature taxonomy). The M-Library web dashboard was used to query candidate processes for producing these features, given the feature type and the material and shape of the raw stock. Figure 3.38 illustrates a schema query being formulated in the web dashboard. Query results are shown in Figure 3.39. For each feature type (column), the table in Figure 3.39 lists the candidate processes.

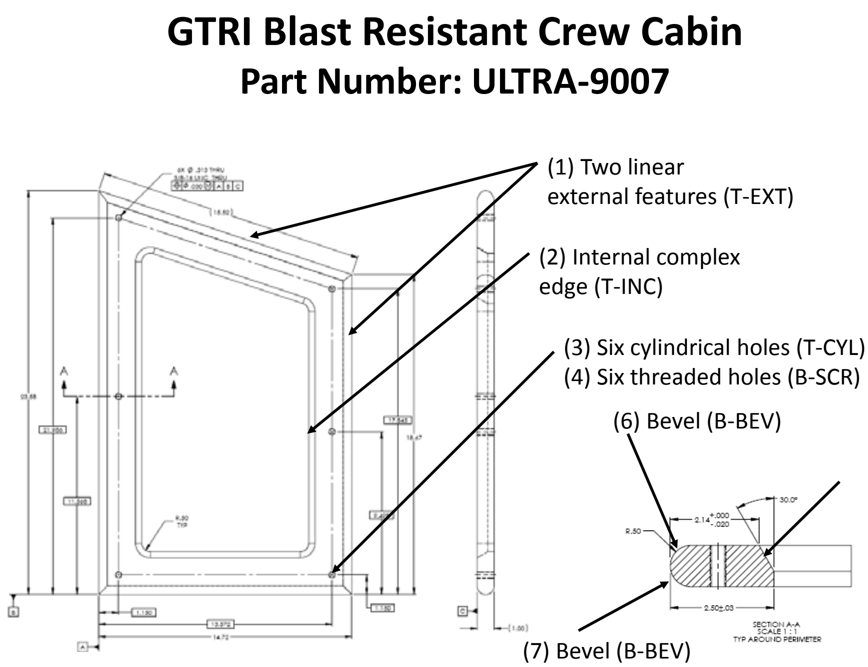


Figure 3.37: Specific part (ULTRA-9007) selected as the challenge problem.

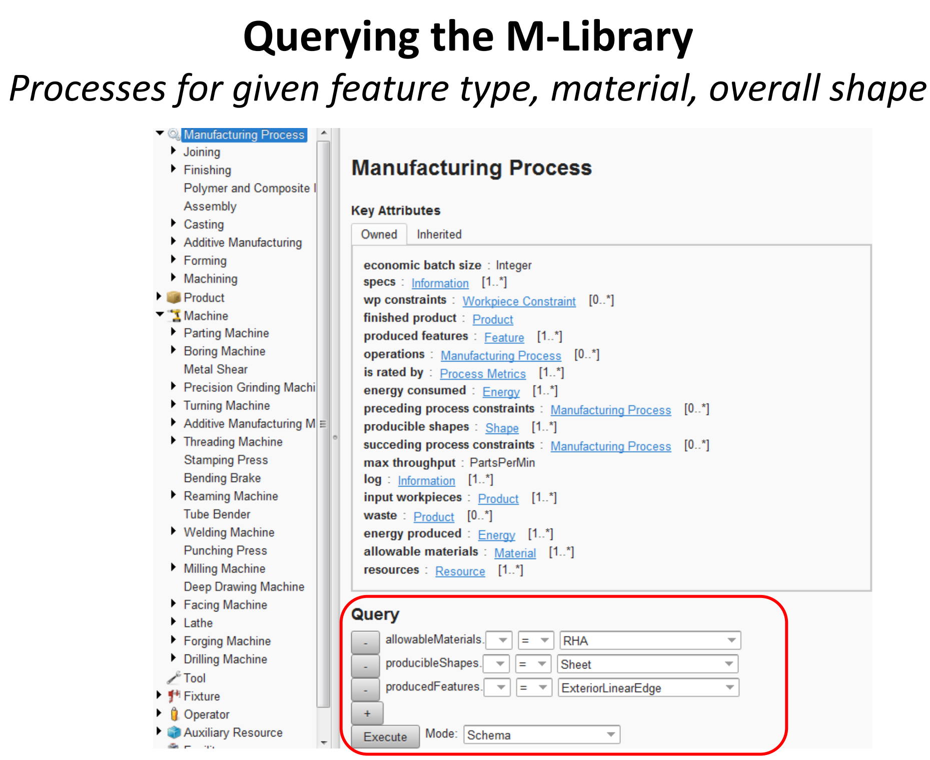


Figure 3.38: Use of M-Library to query processes for a given feature type, material, and raw stock shape.

Feature Type	T-EXL	T-INC	T-CYL	B-SCR	B-BEV	B-BEV	B-BEV
Candidate Operations	WTJ	WTJ	DRP	DRP	CNB	CNB	CNB
	WEM	WEM	WTJ	CND	WEM		
	CNE	CNE	WEM				
	LSC	LSC	CNE				
	SHE		CND				
	BNS		LSC				

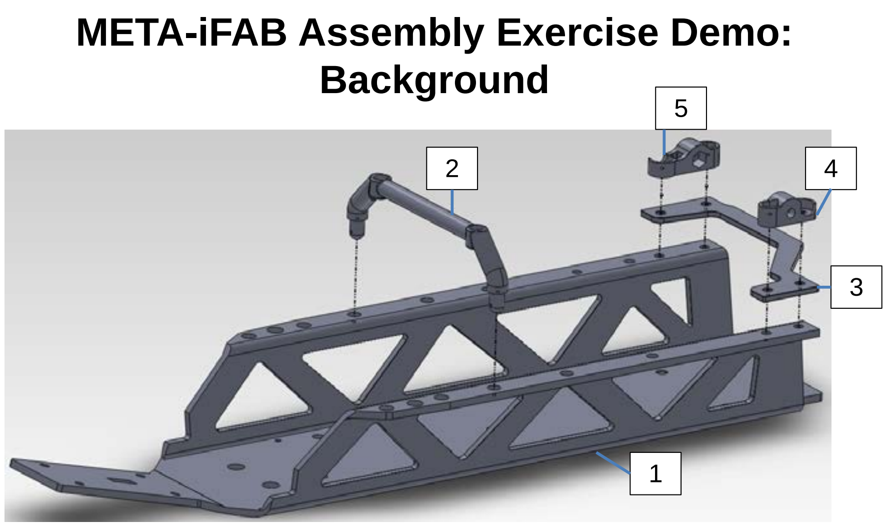
Process/Machine Codes:

WTJ: Waterjet cutting; WEM: Wire EDM; CNE: CNC End Milling; LSC: Laser Cutting; SHE: Shearing; BNS: Sawing; DRP: Drilling; CND: CNC Drilling; CNB: Ball End Milling;

Figure 3.39: Results of M-Library query.

iFAB Assembly Challenge Problem 1 (Jan 2012 PI Meeting, Camp Pendleton)

Figure 3.40 illustrates the iFAB Assembly Challenge Problem 1 which was provided by DARPA to demonstrate M-Library capabilities at the Jan 2012 PI meeting in Camp Pendleton.



ID #	Part Name	Material	Length (mm)	Width (mm)	Height (mm)	Volume (mm³)
1	Main Chassis	Aluminum	464.6	143	54	268623
2	CenRollBarSet	Plastic	138.6	11	39.5	12038.2
3	Rear Brace	Aluminum	143	7	2.9	7866.24
4	4 Radio Box Set	Plastic	32.9	13.1	13.8	2486.77
5	8 Radio Box Set	Plastic	42.1	12	14	3255.71

Figure 3.40: iFAB Assembly Challenge Problem 1 (Jan 2012 PI Meeting).

The use of M-Library for this challenge problem is presented here as a series of queries that a process planner would pose to the M-Library. The responses obtained from the M-Library are also presented. The first set of queries (Queries 1-4) is related to the metal part 1 (Main Chassis) in the assembly. All four queries are of the following type: *What manufacturing processes can produce feature X on the metal part 1*? Here, X refers to the specific types of feature on part 1 as shown in

Figure 3.41 below. The M-Library returns a list of processes for each type of feature as also shown in Figure 3.42. These processes range from traditional machining processes (e.g. Drilling and Milling) to non-traditional processes such as Abrasive Water Jet Machining. The query execution leverages the relationships between processes and features in the M-SysML knowledge graph to come up with the responses. Given the processes returned by the M-Library, a user (process planner) could further query the machines, tools, fixtures, operators, and other auxiliary resources required for the subject processes.

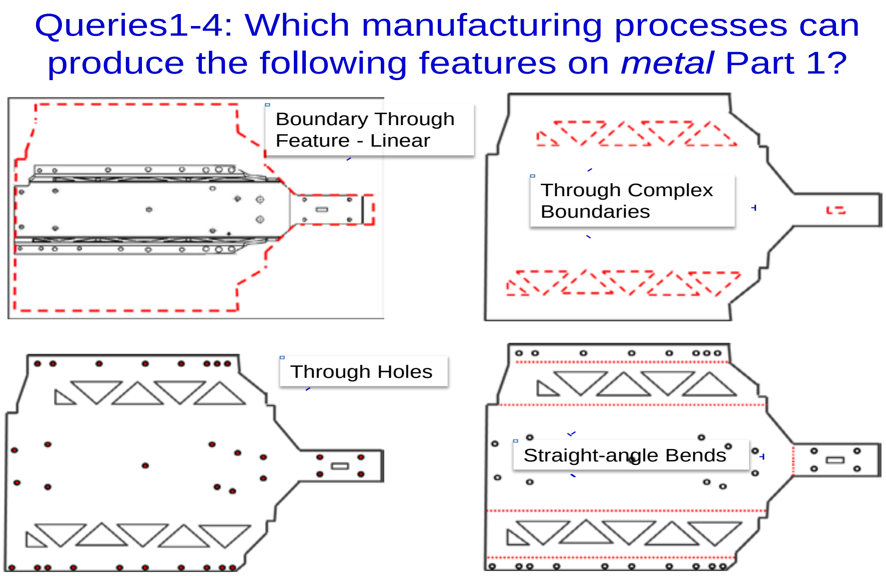


Figure 3.41: Query 1-4

Processes returned by Queries 1-4

Query 1 Boundary Through Feature – Linear	Query 2 Through Complex Boundary	Query 3 Through Hole	Query 4 Straight-angle Bend
• Abrasive Water Jet Machining • Closed-die Forging • Edging • Incremental Forging • Laser Cutting • Milling • Punching • Sawing • Shearing • Wire EDM	• Abrasive Water Jet Machining • Closed-die Forging • Impression-die Forging • Laser Cutting • Milling • Punching • Sinker EDM • Wire EDM	• Abrasive Water Jet Machining • Boring • Drilling • Laser Cutting • Milling • Piercing • Punching • Sinker EDM • Wire EDM	• Closed-die Forging • Impression-die Forging • Straight-angle Bending

Figure 3.42: Results of query 1-4 – Process that can produce specified features on part 1.

The next set of queries involve finding out processes that can produce complex boundary through features on *metal* part 3 (Rear Brace) and *plastic* part 4 (Radio Box Set), as illustrated in Figure 3.43

and 3.44 respectively. The breadth and depth of M-Library is demonstrated here in the range of processes returned in response (Figure 3.45). The results for plastic Part 4 show non-traditional machining processes, additive manufacturing processes, and polymer and composite manufacturing processes. Given the processes returned by the M-Library, a user (process planner) could further query the machines, tools, fixtures, operators, and other auxiliary resources required for the subject processes.

Query 5: Which manufacturing processes can produce Boundary Through Feature (Complex) on *metal* Part 3?

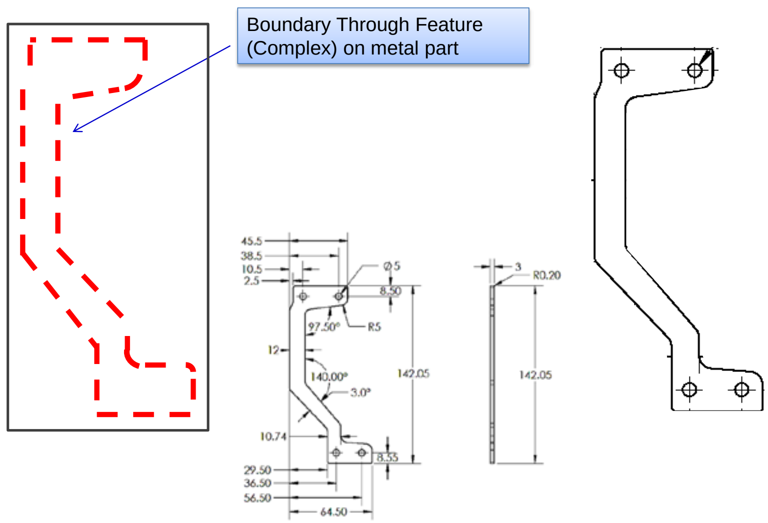


Figure 3.43: Query 5.

Query 6: Which manufacturing processes can produce Boundary Through Feature (Complex) on *plastic* Part 4?

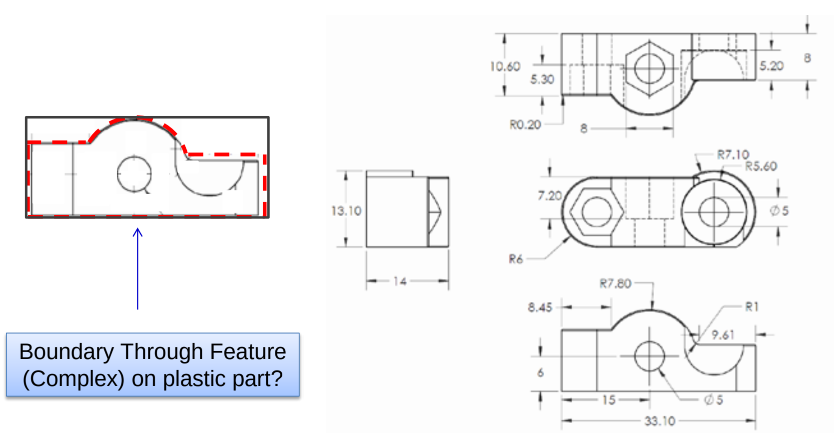


Figure 3.44: Query 6.

Processes returned by Queries 5-6

- Abrasive Water Jet Machining
- Closed-die Forging
- Edging
- Impression-die Forging
- Laser Cutting
- Milling
- Punching
- Sawing
- Wire EDM

- Abrasive Water Jet Machining
- GMT Compression Molding
- Ink-Jet Printing
- Laser Cutting
- Milling
- Prepeg Lay-up
- Punching
- Resin Infusion
- SMC Compression Molding
- Sawing
- Spray-up
- Stereolithography
- Structural Reactive Injection Molding (SRIM)
- Thermoplastic Injection Molding
- Wet Lay-up

Figure 3.45: Processes that can produce complex boundary through features on part 3 (metal) and part 4 (plastic).

The next query demonstrates the ability of M-Library for assembly processes. The query involves identifying machines and tools that can be used for fastening Parts 1, 3, 4 (or 1, 3, 5) with Hex/Square Head Bolt with Hex/Square Head Nut (Figure 3.46). The list of machines and tools returned by the M-Library are shown in Figure 3.47 below. Figure 3.48 shows illustrations of some of the machines and tools in the list.

Query 7: What machines/tools can be used to fasten together parts 1,3,4 (or 1,3,5) with Hex/Square Head Bolt with Hex/Square Head Nut?

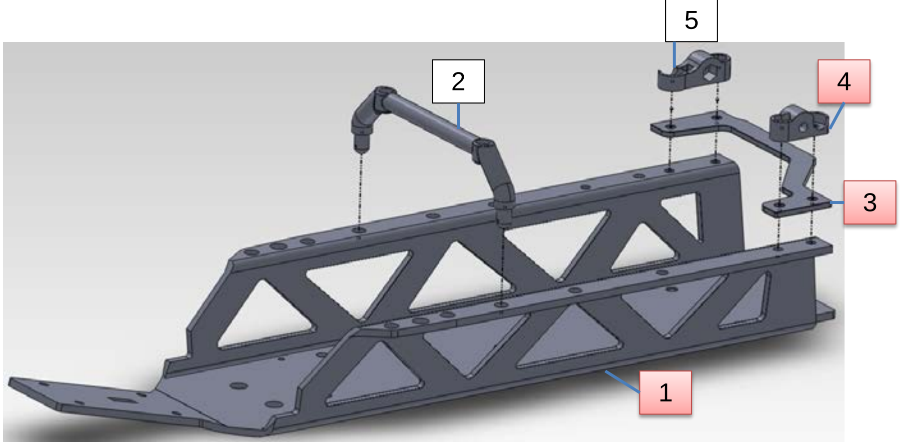


Figure 3.46: Query 7.

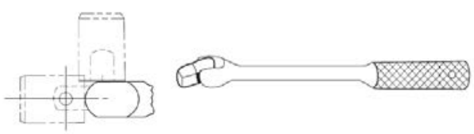
Machines returned by Query 7

Query 7
Machines/Tools that can be used to fasten parts 1,3,4 (or 1,3,5) with Hex/Square Head Bolt with Hex/Square Head Nut

- Adjustable Wrench
- Box Wrench
- Brace Type, Single Revolving Hand Grip Speeder Handle with Socket Wrench
- Combination Wrench
- Electric Impact Wrench with Socket Wrench
- Electric Ratchet Wrench with Socket Wrench
- Flare Nut Wrench
- Hinged Handle with Socket Wrench
- Open End Wrench
- Pneumatic Impact Wrench with Socket Wrench
- Pneumatic Ratchet Wrench with Socket Wrench
- Ratcheting Box Wrench
- Reversible Ratchet Handle with Socket Wrench
- Sliding T-Handle with Socket Wrench
- Spin Type Screwdriver Grip Speeder Handle with Socket Wrench
- Torque Wrench with Socket Wrench

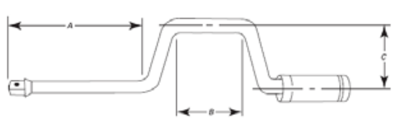
Figure 3.47a: M-Library query results for Query 7.

Fastening Machine/Tools

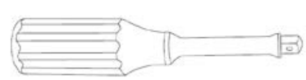


Hinged handle for use in driving socket wrenches. Complete handle (right) and detailed view of the hinge mechanism (left). Source: ANSI/ASME B107.10-2005

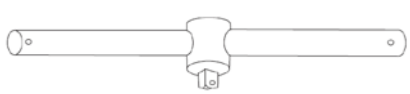
Reversible ratchet handle for use in driving socket wrenches. Source: ANSI/ASME B107.10-2005



Brace Type Single Revolving Hand Grip Speeder Handle. Source: ANSI/ASME B107.10-2005



Spin Type Screwdriver Grip Speeder Handle. Source: ANSI/ASME B107.10-2005



Sliding T-Handle handle for use in driving socket wrenches. Source: ANSI/ASME B107.10-2005

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Figure 3.47b: Illustrations of Machines/Tools returned by Query 7.

iFAB Assembly Challenge Problem 2 (Mar 2012 PI Meeting, Purdue University)

Figure 3.48 illustrates the iFAB Assembly Challenge Problem 2 that was provided by DARPA to demonstrate M-Library capabilities at the Mar 2012 PI meeting at Purdue University.

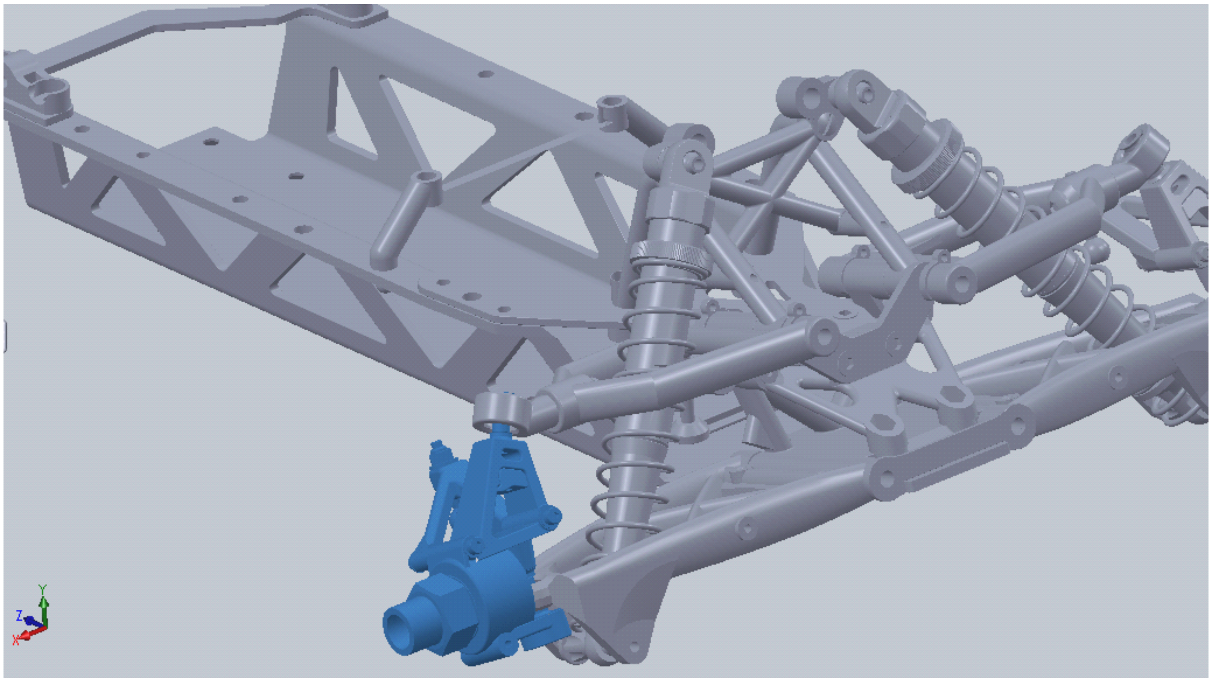


Figure 3.48: iFAB Assembly Challenge Problem 2.

Refer to Appendix 3B for a detailed presentation of M-Library queries and results for this challenge problem.

5.0 Discussion

Given that the M-Library and MACME software were developed in a fast-paced twelve month project, no time was available to mature the final software (and its knowledge content). Consequently, the library, in its current state, has gaps in process knowledge as well as gaps in software features that could potentially simplify and streamline use of the library in support of automated process planning. The main limitations are listed below along with brief suggestions for addressing them:

- ***Process-feature mapping***: As discussed in the report, automated process selection based on the geometric and material information contained in a META generated technical data package for a fabricated parts requires a feature taxonomy and a process-feature mapping for each process capable of producing the features contained in the taxonomy. The feature taxonomy developed in this project, while extensive, is limited to feature labels which imply a specific shape. While this process-feature mapping is in many cases adequate to identify candidate processes for producing the feature(s) in question, it does not account for additional quantitative discriminators that can permit a more refined process selection. For instance, while laser drilling, waterjet cutting, and mechanical drilling can all produce a hole in a metal plate, each process is limited in the size and material in which it can create the hole. The process-feature mappings contained in the M-Library should be expanded to include such size and material related discriminators for each feature in the taxonomy (and any additional feature added in the future). In addition, the process-feature mappings for each process in the M-Library would need to be updated by updating the M-SysML knowledge graph that embodies this knowledge.
- ***Process/Machine schemas:*** While a large number of common manufacturing processes are modeled in the M-Library, future use of the library in the iFAB Foundry effort may require modification of some of the process/machine schemas to include/exclude certain process/machine attributes before instance data for the particular process/machine can be added to the library. This will require the schema (M-SysML knowledge graph) to be suitably edited in a SysML editor (e.g. Magic Draw). The library user should compare the attributes of the process/machine schemas contained in the library with the process/machine attributes of the foundry to be instantiated in order to determine the modifications required.
- ***Instance data:*** A fairly large number of instances of the various processes/machines have been populated in the M-Library from standard sources (e.g. books, papers, equipment vendor websites, etc.). The viability of the instance data for the specific library application under consideration should be confirmed prior to using the data. It is suggested that the instance data contained in the current version of the M-Library be replaced with new instance data relevant to the various iFAB Foundry performers.
- ***Time and cost models:*** Only a limited number of simple time and cost models for unit processes were incorporated into the MACME software for library validation purposes.

Since detailed time and cost analyses require a detailed process plan, which was outside the scope of the GT iFAB effort, it is recommended that the iFAB Foundry performer consider using powerful commercial cost estimators (e.g. see http://www.apriori.com/, SEERMfg at http://www.galorath.com/) for this purpose. Note that for CNC machining operations, commercial Computer Aided Manufacturing (CAM) software can easily provide time calculations from the NC toolpath information generated by the CAM software.

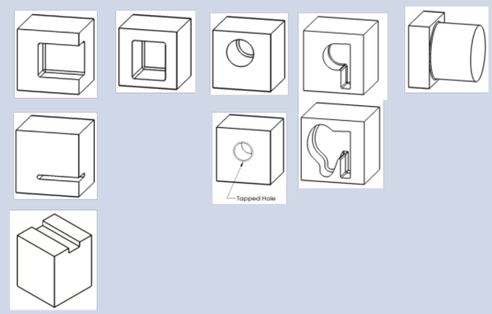
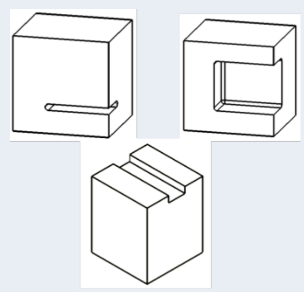
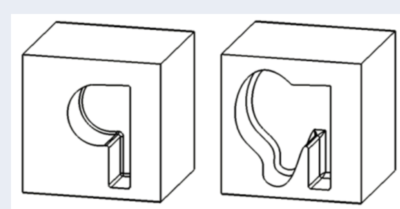
- ***Process modeling/planning software environment:*** The current version of the library can be accessed via a web dashboard or via an API. However, a process planner would greatly benefit from a process modeling/planning software environment that is directly linked to the M-Library and has a "drag-and-drop" feature that permits the construction and time/cost analyses of alternate process plans by dragging and dropping unit processes from the library into the modeling environment. It is recommended that such an environment be developed and linked to the M-Library.

6.0 Conclusion

This iFAB project has resulted in the development of a prototype manufacturing process library software (M-Library) for modeling the manufacturing capabilities of foundries used to manufacture military ground vehicles. As designed, the software tool supports interactive and automated queries about for automated process selection. During the course of the development, several component fabrication examples were used to test and demonstrate the capabilities of the M-Library in supporting automated process selection. The report documented the various tasks and approaches undertaken to generate/acquire the knowledge embedded in the M-Library as well as the methods and tools used to architect the library software. It is anticipated that the library software will be further developed and utilized in the follow-on iFAB Foundry effort.

APPENDIX 1 (Task 2a)

Table A2a.1: Definitions of Negative Features.

Classification	Feature Name	Characterization	Depiction
Negative Feature	Blind Feature	A cavity in the surface of a part set to a specific depth.	
Negative Feature	Blind Slot	A cavity in the surface of a part set to a specific depth that is not fully enclosed by the surface boundary.	
Negative Feature	Blind Revolute	A revolved cut to a specific depth.	
Negative Feature	Blind Complex Pocket	A cavity in the surface of a part set to a specific depth with an intricate cross section that can be described by a multitude of curvilinear edges that is fully enclosed by the surface boundary. A subset of “Blind Pocket” feature.	

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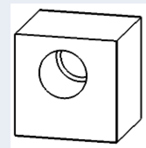
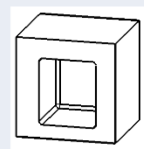
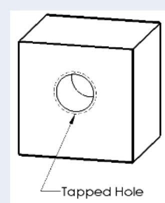
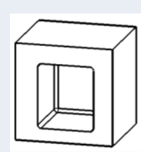
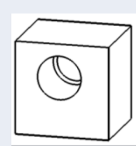
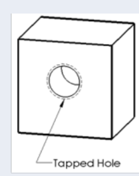
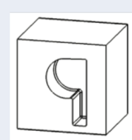
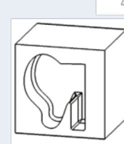
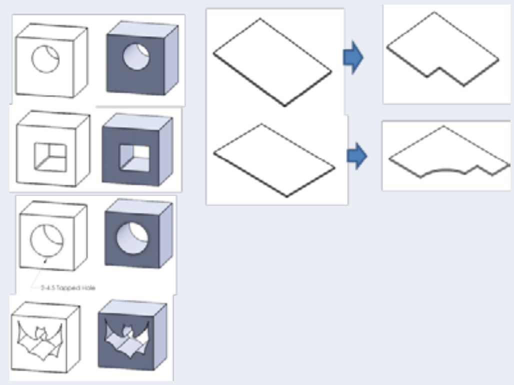
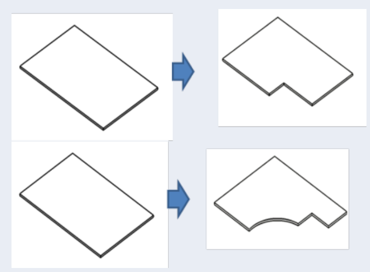
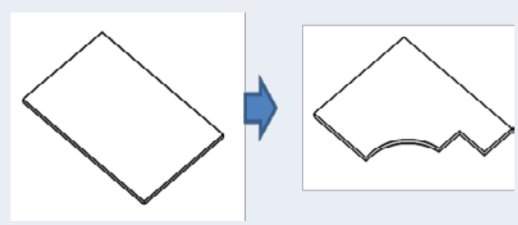
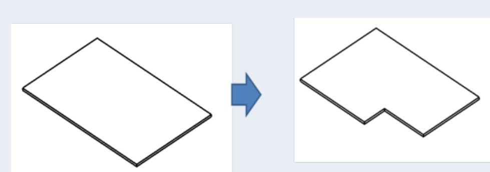
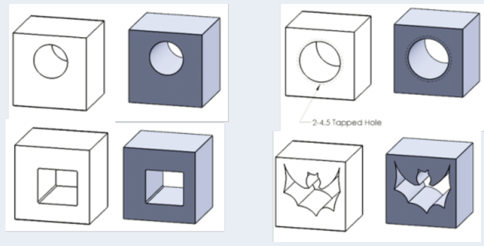
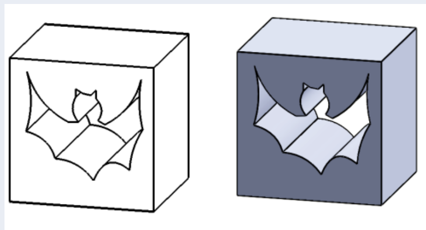
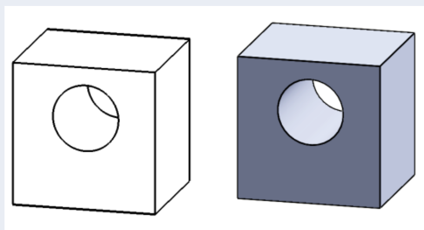
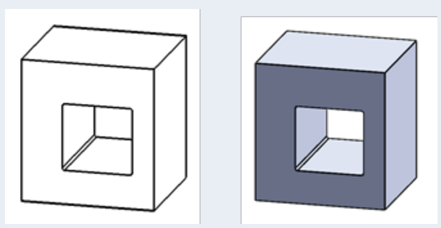
Negative Feature	Blind Hole	A cavity in the surface of a part with a circular cross section set to a specific depth that is fully enclosed by the surface boundary.	
Negative Feature	Blind Linear Pocket	A cavity in the surface of a part with a rectangular cross section set to a specific depth that is fully enclosed by the surface boundary.	
Negative Feature	Blind Screw Thread	A threaded cavity in the surface of a part with a circular cross section set to a specific depth that is fully enclosed by the surface boundary.	
Negative Feature	Blind Pocket	A cavity in the surface of a part set to a specific depth that is fully enclosed by the surface boundary.	    

Negative Feature	Through Feature	A cut through the thickness of the part.	
Negative Feature	Boundary Through Feature	A through cut of the part's profile (or boundary).	
Negative Feature	Boundary Through Feature – Complex	A through cut of the part's profile on an intricate path that can be described by a multitude of curvilinear edges.	
Negative Feature	Boundary Through Feature – Linear	Linear through cut or cuts of the part's profile.	

Negative Feature	Interior Through Feature	A cut through the thickness of the part fully enclosed by the surface boundary.	
Negative Feature	Through Complex Boundary	A through cut with an intricate cross section that can be described by a multitude of curvilinear edges fully enclosed by the surface boundary.	
Negative Feature	Through Hole	A through cut with a circular cross section fully enclosed by the surface boundary.	
Negative Feature	Through Linear Boundary	A through cut with a rectangular cross section fully enclosed by the surface boundary.	

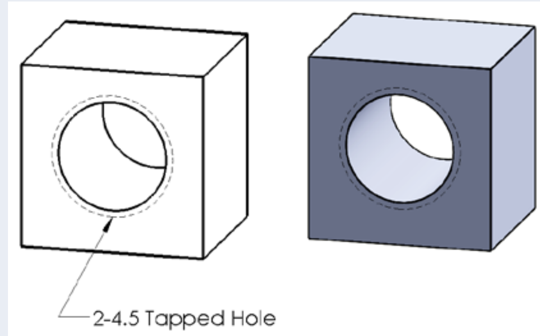
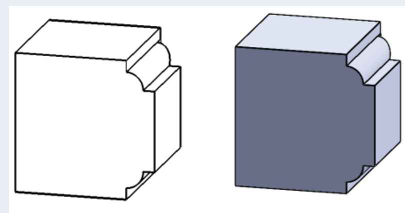
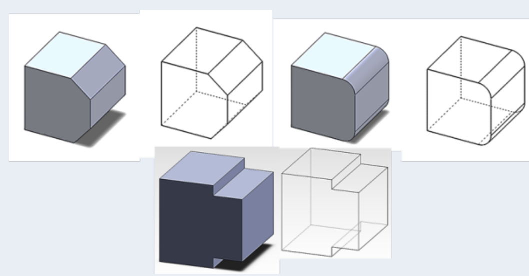
Negative Feature	Through Screw Thread	A threaded through cut with a circular cross section fully enclosed by the surface boundary.	
Negative Feature	Complex Edge Feature	A cut along an edge of the part that can be described by a multitude of curvilinear edges. A subset of “Edge Feature”.	
Negative Feature	Edge Feature	A cut along an edge of the part.	

Table A2a.2. Nomenclature for machining time and cost equations.

Variable	Definition	Units	Variable	Definition	Units
a_p	diameter of hole	mm	N	spindle speed	rpm
a_p,plunge	plunge grinding-width of grinding wheel	mm	n	tool life constant. work/tool material dependant	n/a
a_p,traverse	traverse grinding-depth of cut	mm	n_f	no. of flutes	#
b	depth of cut	mm	n1	tool life constant. work/tool material dependant	n/a
b_w	width of workpiece	mm	n2	tool life constant. work/tool material dependant	n/a
C	cost	$	T	tool life	min.
C_1	Nonproductive cost per component	$/piece	T_ac	cutting time per component	min.
C_2	Cost of machining time	$	T_c	machining time per component	min.
C_3	Cost of tool changing time	$	T_d	time to change a cutting edge	min.
C_4	Cost of tool per component	$/piece	T_drilling	time for drilling	min.
C_5	Cost of materials	$	t_eq	equivalent chip thickness	mm
C_II	cost	$	T_facing	time for facing	min.
C_T	Cost per piece	$/piece	T_L	nonproductive time	min.
d	depth of cut	mm	T'_L	time to return and set tool for second past	min.
D	diameter of workpiece	mm	t_m	max undeformed chip thickness	mm
D_mill	diameter of cutter	mm	T_T	Time per component for max production rate	min./piece
D_s	diameter of grinding wheel	mm	T_vm	Tool life for min. cost per component	min.
f	feed	mm/rev	T_vp	Tool life for max production rate	min.
K	tool life constant	n/a	V	cutting speed	sfpm
K_r	major cutting edge angle	º	v	feed rate	mm/min
K_T	number of teeth on cutter	#	v_f	axial advancing speed of drill into workpiece	mm/rev
l	distance traveled	mm	v_trav	velocity of workpiece	mm/min
L	length of workpiece	mm	x	cost rate	$
l_w	length of hole	mm	y	tool cost per cutting edge	$

<u>Minimum Cost of Single Point Cutting Processes</u>

The cost per part for single point cutting processes is provided in Equation 2a.1 supported by information from Equations 2a.2 through 2a.7. This particular equation is for single pass cases. Refer to Table 2a.2 for variable nomenclature. The values of x, T_L, T_d, and y are found from cost data and standard times usually provided by the user.

$$C_T = C_1 + C_2 + C_3 + C_4 + C_5 \quad \text{(Eqn. A2a.1)}$$

$$C_1 = xT_L \quad \text{(Eqn. A2a.2)}$$

$$C_2 = xT_c \quad \text{(Eqn. A2a.3)}$$

$$C_3 = xT_d\left(\frac{T_{ac}}{T_{vm}}\right) \quad \text{(Eqn. A2a.4)}$$

$$C_4 = y\left(\frac{T_{ac}}{T_{vm}}\right) \qquad \text{(Eqn. A2a.5)}$$

$$C_5 = material\ costs \qquad \text{(Eqn. A2a.6)}$$

$$T_{vm} = \frac{A}{V^{1/n} f^{1/n1}} = \left(\frac{1}{n} - 1\right)\left(\frac{xT_d + y}{x}\right) \qquad \text{(Eqn. A2a.7)}$$

The cutting conditions are found in terms of the tool life T_{vm} associated with the optimum speed V defined in,

$$V = \frac{A^n}{T_{vm}^n f^{n/n1}} \qquad \text{(Eqn. A2a.8)}$$

where the feed f is given the highest possible value. The machining time T_c of single pass turning operations are approximately equal to the actual cutting time T_{ac} and calculated using Equation 2a.9.

$$T_c = \frac{l}{fN} = \frac{l}{\lambda V f} = \frac{\pi D l}{12 V f} \cong T_{ac} \qquad \text{(Eqn. A2a.9)}$$

<u>Maximum Production Rate of Single Point Cutting</u>

In cases when it is necessary to perform machining operation at maximum production rates the time per component is minimum. The time per component for single-pass turning operations is calculated using,

$$T_T = T_L + \frac{l}{\lambda V f} + \frac{T_d l}{\lambda A} V^{\left(\frac{1}{n}\right)-1} f^{\left(\frac{1}{n1}\right)-1} \qquad \text{(Eqn. A2a.9)}$$

$$T_{vp} = \frac{A}{V^{1/n} f^{1/n1}} = \left[\frac{1}{n} - 1\right] T_d \qquad \text{(Eqn. A2a.10)}$$

$$T_{ac} \cong \frac{\sqrt{(d/D_{mill})}\,l}{\pi v} \qquad \text{(Eqn. A2a.11)}$$

$$V = \frac{K}{[T_d(\frac{1}{n}-1)]^n} \qquad \text{(Eqn. A2a.12)}$$

<u>Multi-pass Single Point Cutting</u>

The majority of single point cutting operations require a roughing pass to remove the bulk of material and then a finishing pass to acquire desired surface finish. The cost equation for such circumstances is displayed in Equation 2a.13.

$$C_{II} = xT_L + xT'_L + x\frac{l}{\lambda}\left[\frac{1}{V_r f_r} + \frac{1}{V_f f_f}\right] + \frac{l}{\lambda}[xT_d + y]\left[\frac{V_r^{(1/n)-1} f_r^{(1/n1)-1} b_r^{1/n2} + V_f^{(1/n)-1} f_f^{(1/n1)-1} b_f^{1/n2}}{K}\right]$$

(Eqn. A2a.13)

<u>Single-pass Milling Operations</u>

Similar to single point cutting operations, there are equations to calculate the desired cost and time for multiple pass operations. It is assumed that the depth of cut and width of cut are provided and fixed. The tool life equation for peripheral is given by,

$$T = \frac{A}{V^{1/n} t_{eq}^{1/n1}} \qquad \text{(Eqn. A2a.14)}$$

$$t_{eq} = \frac{t_m}{\left[\left(\frac{1}{n1}+1\right)\right]^{n1}} \qquad \text{(Eqn. A2a.15)}$$

$$t_m \cong \frac{2v}{NK_T}\sqrt{\frac{d}{D}} \qquad \text{(Eqn. A2a.15)}$$

and the cutting velocity (in SI units) is found using equation 2a.16 and the actual milling cutting time is calculated using equation 2a.17.

$$V = \frac{\pi DN}{1000} \qquad \text{(Eqn. A2a.16)}$$

$$T_{ac} \cong \frac{\sqrt{(d/D_{mill})}l}{\pi v} \qquad \text{(Eqn. A2a.17)}$$

The cost per component is calculated using during milling operations is then calculated using,

$$C = xT_L + x\frac{l}{v} + [xT_d + y] \cdot \frac{\left(\frac{\pi}{12}\right)^{\frac{1}{n}} 2^{1/n1} l}{A\left(\frac{1}{n1}+1\right)\pi K_T^{\frac{1}{n1}}} d^{(1/2n1)+(1/2)} D^{(1/n)-(1/2n1)-(1/2)} N^{(1/n)-(1/n1)} v^{(1/n1)-1}$$

(Eqn. A2a.18)

Miscellaneous time calculations

The machining time calculations for facing, drilling and grinding processes are given below.

$$T_{facing} = \frac{D}{2fN} \qquad \text{(Eqn. A2a.19)}$$

$$T_{drilling} = \frac{l_w + \frac{a_p}{n_f}\cot K_r}{v_f} \qquad \text{(Eqn. A2a.20)}$$

$$T_{grinding} = \frac{b_w}{2fn_r} \qquad \text{(Eqn. A2a.21)}$$

$$n_r = \frac{v_{trav}}{2[L+2\sqrt{\left(\frac{D_s}{2}\right)^2 - \left(\frac{D_s}{2}-a_p\right)^2}} \qquad \text{(Eqn. A2a.22)}$$

Time and Cost Equations for Selected Nontraditional Machining Processes

The time per component for wire EDM, abrasive waterjet machining and laser cutting operations are calculated as follows.

Wire EDM:

$$T_{wireedm} = \frac{4\times10^4 I_{edm} T_m{}^{-1.23}}{dw} l \qquad \text{(Eqn. A2a.23)}$$

Abrasive waterjet machining:

$$T_{awj} = ul \qquad \text{(Eqn. A2a.24)}$$

Laser cutting:

$$T_{laser} = \frac{P}{\frac{\pi}{4} E (f\alpha)^2 d} l \qquad \text{(Eqn. A2a.25)}$$

Variable	Definition	Units	Variable	Definition	Units
α	laser beam divergence	rad	l	distance traveled	mm
d	depth of cut	mm	P	laser power	W
E	vaporization energy of material	W /mm^3	T_m	melting point of material	℃
f	focal length of the lens	mm	u	traverse speed of cutting head	mm/s
I_edm	EDM current	A	w	width of cut	mm

The cost per part for the processes is computed from the following equations. The values of x, T_L, T_d, T_{vm} and y are found from cost data and standard times usually provided by the user. T_c is approximately equal to T_{ac}, and can be found from the three time models above.

$$C_T = C_1 + C_2 + C_3 + C_4 + C_5 \qquad \text{(Eqn. A2a.26)}$$

$$C_1 = xT_L$$

$$C_2 = xT_c$$

$$C_3 = xT_d\left(\frac{T_{ac}}{T_{vm}}\right)$$

$$C_4 = y\left(\frac{T_{ac}}{T_{vm}}\right)$$

$$C_5 = material\ cost$$

Table A2a.3: List of materials considered for time and cost analysis.

Material	Specific Material	Hardness	MDH: Hardness Range	
		Brinell	*Low*	*High*
Carbon steel				
	Carbon Steel A709 Grade 50	269		
	AISI 1020	143	100	150
	AISI 1090 Steel, hot rolled, 19-32 mm round	248		
Military Spec				
	MIL-A-46100 Steel Plate	530		
	MIL-A-46063 Heat Treated Aluminum Armor	133		
	MIL-S-12560	255	250	300
	MIL-S-16216	255	250	300
	HY80	225	200	250
	HY100	325	300	350
Cast Iron				
	Ductile Cast Iron, ASTM A536 65-45-12		140	190
	Gray Cast Iron, ASTM A48 -40		190	220
Aluminum 1000				
	Aluminum 1100-H12	28	30	80
	Aluminum 1100-O	23	30	80
Aluminum 2000				
	Aluminum 2014-T6	154	75	150
	Aluminum 2024-T6	153	75	150
	Aluminum 2139-T8	140	75	150

Aluminum 5000				
	Aluminum 5040		75	150
	Aluminum 5052-H36	86	75	150
Aluminum 6000				
	Aluminum 6061-T6	105	75	150
Aluminum 7000				
	Aluminum 7075-T6	165	75	150
Titanium Alloy				
	Ti-6Al-4V	379	320	380
	Ti-6Al-2Sn-4Zr-2Mo	318	320	380
Monel				
	Special Metals MONEL Alloy 400	140	115	240
	Special Metals MONEL Alloy K-500	265	150	320

Material	**Specific Material**	**Hardness**	**MDH: Hardness Range**	
		Brinell	***Low***	***Brinell***
Inconel				
	Inconel 600	165	140	220
	Inconel 625	222	200	300
	Inconel 718	336	300	400
Hastelloy				
	G-30 alloy mill annealed	128	140	220
	G-50 alloy Grade 140 N--Cr-Fe-Mo Alloy	346	240	310

APPENDIX 2 (Task 2d)

Build Time Algorithm

Table A2d.1 Terminology for Build Time Algorithm (provided means from database)

pt_length	part length (user's input)
pt_width	part width (user's input)
pt_height	part height (user's input)
af	area factor (computed)
vol_bb	volume of part bounding box (computed)
actVol	actual part volume (user's input)
alpha	1.5 (provided)
area_function	area function (computed)
area_avg	average area (computed)
gap	gap between parts (provided)
vat_height	maximum height of a part that a machine can achieve (provided)
vat_length	maximum length of a part that a machine can achieve (provided)
vat_width	maximum width of a part that a machine can achieve (provided)
vat_vol	maximum volume that a machine can achieve (computed)
pts_vol	part volume (computed)
multpart	dimension of part distribution in the machine (either 2 or 3, provided)
npx	number of parts in x direction in machine (computed)
npy	number of parts in y direction in machine (computed)
npz	number of parts in z direction in machine (computed)
N_build	total number of parts that can be built at a time (computed)
angle (rad)	angle of part orientation (provided)
z_height	total height of part (computed)
supp_height	support height (computed)
d_scan	diameter of scan (provided)

supp_factor	support factor (provided)
lparea	intermediate variable (computed)
npxsec	intermediate variable (computed)
lsarea	intermediate variable (computed)
nsxsec	intermediate variable (computed)
l_scan	total length to be scanned (computed)
layerThickness_min	minimum layer thickness (provided)
layerThickness_max	maximum layer thickness (provided)
numScanPart	number of scans for part (provided)
numScanSupp	number of scans for support (provided)
vel_scan_min	minimum scan velocity (provided)
vel_scan_max	maximum scan velocity (provided)
vel_jump	velocity of laser or nozzle when jumping from part to part (provided)
vel_avg_min	minimum average scan velocity (computed)
vel_avg_max	maximum average scan velocity (computed)
hatchSpacing	scan vector overlap (%) (provided)
t_scan_min	minimum scan time (computed)
t_scan_max	maximum scan time (computed)
t_pre	pre-dip delay (provided)
t_z_down	platform down movement time (provided)
t_z_delay	delay between down and up movement (provided)
t_z_up	platform up movement time (provided)
t_post	(provided)
t_wait	z-wait time (provided)
t_sweep	material deposition time (provided)

t_preproc	pre-processing time (provided)
t_postproc	post-processing time (provided)
t_startup	machine startup time (provided)
f	0.5, build time factor (provided)
t_build_min	minimum build time (computed)
t_build_max	maximum build time (computed)

Build Time Algorithm

1. vol_bb = pt_length*pt_height*pt_width
2. af = actVol/vol_bb
3. area_function = af*exp(alpha*(1-af))
4. area_avg = vol_bb*area_function/pt_height
5. pts_vol = (pt_length + gap) * (pt_width + gap) * (pt_height + gap)
6. npx = 1, npy = 1, npz = 1
7. if ((multpart) == 2)

   {

   a. npx = floor(vat_length / (pt_length + gap));
   b. npy = floor(vat_width / (pt_width + gap));

   }

8. else if (multpart == 3)

   {

   a. npx = floor (vat_length / (pt_length + gap));
   b. npy = floor (vat_width / (pt_width + gap));
   c. npz = floor (vat_height / (pt_height + gap));

   }

9. N_build = npx * npy * npz
10. z_height = pt_length * sin(angle) + pt_height * cos(angle)
11. supportHeight = 4 * layerThickness_min
12. lparea = N_build * area_avg / d_scan
13. npxsec = (pt_height - supportHeight) / layerThickness_min
14. lsarea = N_build * area_avg * supp_factor / d_scan
15. nsxsec = supportHeight / layerThickness_min

16. l_scan = numScanPart * lparea * npxsec + numScanSupport * lsarea * nsxsec
17. vel_avg_min = vel_scan_min * area_function + vel_jump * (1 - area_function)
18. vel_avg_max = vel_scan_max * area_function + vel_jump * (1 - area_function)
19. t_scan_min = l_scan / (3600 * vel_avg_max * hatchSpacing)
20. t_scan_max = l_scan / (3600 * vel_avg_min * hatchSpacing)
21. t_delay = (z_height / layerThickness_min) * (t_pre + t_z_down + t_z_delay + t_z_up + t_sweep + t_wait) / 3600.0
22. t_build_min = f * (t_scan_min + t_delay + t_startup)
23. t_build_max = f * (t_scan_max + t_delay + t_startup)

Cost Model

Table 2d.2 Terminology for Cost Model

density	material density (provided)
matl_cost	material cost (provided)
C_matl	material cost per part(computed)
N_ppd_min	minimum number of parts per day (computed)
N_ppd_max	maximum number of parts per day (computed)
Nmach	number of machines
maint_cost	maintenance cost per machine (provided)
C_maint_min	minimum total maintenance cost per year (computed)
C_maint_max	maximum total maintenance cost per year (computed)
mach_rate	cost of running machine (provided)
ul	useful life (provided)
C_mach_min	minimum machine cost per year (computed)
C_mach_max	maximum machine cost per year (computed)
tech_rate	technical support rate (provided)
C_oper_min	minimum operation cost (computed)
C_oper_max	maximum operation cost(computed)

Cost Model

- C_matl = actVol * density * (1 + supp_factor) * matl_cost * .000001
- N_ppd_min = (24 / t_build_max) * N_build * Nmach
- N_ppd_max = (24 / t_build_min) * N_build * Nmach
- C_maint_min = (maint_cost * Nmach) / (365 * N_ppd_max)
- C_maint_max = (maint_cost * Nmach) / (365 * N_ppd_min)
- C_mach_min = (mach_cost * Nmach)/(365 * ul * N_ppd_max)
- C_mach_max = (mach_cost * Nmach) / (365 * ul * N_ppd_min)
- C_oper_min = (CB.MinBuildTime * mach_rate + (t_preproc + t_postproc) * tech_rate) / N_build
- C_oper_max = (CB.MaxBuildTime * mach_rate + (t_preproc + t_postproc) * tech_rate) / N_build

APPENDIX 3 (Task 2f)

Table A2f.1: Standard Fasteners selected for inclusion in the M-library.

(Note that those highlighted in yellow are currently implemented in the library)

Fastener Name	ANSI/ASME Standard (or other - e.g. SAE, if indicated)
Inch Series Bolts	
Square Bolt	B18.2.1 - 2010
Heavy Hex Structural Bolt	B18.2.6 - 2010
Hex Bolt	B18.2.1 - 2010
Heavy Hex Bolt	B18.2.1 - 2010
Round Head Bolt	B18.5 – 2008
Round Head Square Neck Bolt	B18.5 – 2008
Round Head Short Square Neck Bolts	B18.5 – 2008
Round Head Fin Neck Bolt	B18.5 – 2008
Round Head Ribbed Neck Bolt	B18.5 – 2008
Step Countersunk Square Neck Bolts	B18.5 – 2008
T-Head Bolts	B18.5 – 2008
114-deg Countersunk Square Neck Bolts	B18.5 – 2008
Countersunk Bolts	B18.5 – 2008
Slotted Countersunk Bolts	B18.5 – 2008
Metric Bolts	
Metric Hex Bolt	B18.2.3.5M - 1979 (R2011)
Metric Heavy Hex Bolt	B18.2.3.6M - 1979 (R2006)
Metric Heavy Hex Structural Bolt	B18.2.3.7M - 1979 (R2006)
Metric Round Head Square Neck Bolt	B18.5.2.2M - 1982 (R2010)
Metric Round Head Short Square Neck Bolt	B18.5.2.1M - 2006 (R2011)

Inch Series Screws	
Heavy Hex Screws	B18.2.1 - 2010
Hex Cap Screws	B18.2.1-1996
Hex Flange Screws	B18.2.1 - 2010
100-Degree Flat Countersunk Head Machine Screws	ASME B18.6.3-2010
Slotted Flat Countersunk Head Machine Screws	ASME B18.6.3-2010
Slotted 100-Degree Flat Countersunk Head Machine Screws	ASME B18.6.3-2010
Slotted Close Tolerance 100-Degree Flat Countersunk Head Machine Screws	ASME B18.6.3-2010
Slotted Undercut 82-deg Flat Countersunk Head Machine Screws	ASME B18.6.3-2010
Plain Hex Washer Head Machine Screws	ASME B18.6.3-2010
Slotted Hex Washer Head Machine Screws	ASME B18.6.3-2010
Slotted Truss Head Machine Screw	ASME B18.6.3-2010
Slotted Hex Head Machine Screw	ASME B18.6.3-2010
Hex Head Machine Screw	ASME B18.6.3-2010
Slotted Pan Head Machine Screws	ASME B18.6.3-2010
Slotted Fillister Head Machine Screws	ASME B18.6.3-2010
Slotted Drilled Fillister Head Machine Screws	ASME B18.6.3-2010
Slotted Oval Countersunk Head Machine Screws	ASME B18.6.3-2010
Slotted Binding Head Machine Screws	ASME B18.6.3-2010
Slotted Undercut Oval Countersunk Head Machine Screws	ASME B18.6.3-2010
Slotted Round Head Machine Screws	ASME B18.6.3-2010
Metric screws	
Metric Hex Cap Screw	B18.2.3.1M - 1999 (R2011)
Metric Formed Hex Screw	B18.2.3.1M - 1999 (R2011)
Metric Heavy Hex Screw	B18.2.3.1M - 1999 (R2011)
Metric Heavy Hex Flange Screw	B18.2.3.1M - 1999 (R2011)
Metric Hex Flange Screw	B18.2.3.1M - 1999 (R2011)
Metric machine screws	

Type I Cross Recessed Flat Countersunk Head Metric Machine Screw	B18.6.7M - 1999 (R2010)
Type Ia Cross Recessed Flat Countersunk Head Metric Machine Screw	B18.6.7M - 1999 (R2010)
Type I Cross Recessed Oval Countersunk Head Metric Machine Screw	B18.6.7M - 1999 (R2010)
Type Ia Cross Recessed Oval Countersunk Head Metric Machine Screw	B18.6.7M - 1999 (R2010)
Type I Cross Recessed Pan Head Metric Machine Screw	B18.6.7M - 1999 (R2010)
Type Ia Cross Recessed Pan Head Metric Machine Screw	B18.6.7M - 1999 (R2010)
Slotted Flat Countersunk Head Metric Machine Screw	B18.6.7M - 1999 (R2010)
Slotted Oval Countersunk Head Metric Machine Screw	B18.6.7M - 1999 (R2010)
Slotted Pan Head Metric Machine Screw	B18.6.7M - 1999 (R2010)
Hex Head Metric Machine Screw	B18.6.7M - 1999 (R2010)
Hex Flange Head Metric Machine Screw	B18.6.7M - 1999 (R2010)
Square Recessed Flat Countersunk Head Metric Machine Screw	B18.6.7M - 1999 (R2010)
Square Recessed Oval Countersunk Head Metric Machine Screw	B18.6.7M - 1999 (R2010)
Square Recessed Pan Head Metric Machine Screw	B18.6.7M - 1999 (R2010)
Inch Series Cap, Shoulder, and Set Screws	
Slotted Flat Countersunk Head Cap Screws	B18.6.2-1998 (R2010)
Slotted Round Head Cap Screws	B18.6.2-1998
Slotted Fillister Head Cap Screws	B18.6.2-1998
Socket Head Cap Screws	B18.3-2003
Spline Socket Head Cap Screws	B18.3-2003
Hexagon Socket Flat Countersunk Head Cap Screws	B18.3-2003
Spline Socket Flat Countersunk Head Cap Screws	B18.3-2003
Hexagon Socket Button Head Cap Screws	B18.3-1998
Spline Socket Button Head Cap Screws	B18.3-1998
Socket Head Shoulder Screws	B18.3-1998
Slotted Headless Set Screws	B18.6.2-1998 (R2010)
Hexagon Socket Set Screw	B18.3-1998
Spline Socket Set Screw	B18.3-1998
Square Head Set Screws	B18.6.2-1998 (R2010)

Metric Cap and Shoulder Screws	
Metric Socket Head Cap Screw	B18.3.1M - 1986
Metric Socket Head Shoulder Screw	B18.3.3M - 1986
Metric Flat Head Countersunk Socket Cap Screw	B18.3.5M - 1986
Metric Socket Head Cap Screw, Spline Drive	B18.3.1M - 1986
Metric Button Head Cap Screw	B18.3.4M - 1986
Inch Series Nuts	
Hex Nut	B18.2.2 - R1999
Hex Jam Nut	B18.2.2 - R1999
Heavy Hex Nut	B18.2.2 - R1999
Heavy Hex Jam Nut	B18.2.2 - R1999
Hex Flat Nut	B18.2.2 - R1999
Hex Flat Jam Nut	B18.2.2 - R1999
Heavy Hex Flat Nut	B18.2.2 - R1999
Heavy Hex Flat Jam Nut	B18.2.2 - R1999
Hex Slotted Nut	B18.2.2 - R1999
Heavy Hex Slotted Nut	B18.2.2 - R1999
Hex Thick Slotted Nut	B18.2.2 - R1999
Square Nut	B18.2.2 - R1999
Heavy Square Nut	B18.2.2 - R1999
Hex Thick Nut	B18.2.2 - R1999
Hex High Nut	SAE Standard J482
Hex Slotted High Nut	SAE Standard J482
Metric Nuts	
Metric Slotted Hex Nut	B18.2.4.3M - 1979
Metric Hex Flange Nut	B18.2.4.4M-1982 (R2010)
Prevailing-Torque Metric Hex Flange Nut	B18.16M - 2004
Prevailing-Torque Metric Hex Nut	B18.16M - 2004

Metric Hex Jam Nut	B18.2.4.5M-2008
Metric Heavy Hex Nut	B18.2.6M-2011
Inch Series Washers	
Type A Plain Washers	B18.22.1-1965 (R2003)
Type B Plain Washers	B18.22.1-1965 (R2003)
High Collar Helical Spring Lock Washers	B18.21.1-1999
Helical Spring Lock Washers	B18.21.1-1999
Type A Internal-External Tooth Lock Washers	B18.21.1-1999
Type B Internal-External Tooth Lock Washers	B18.21.1-1999
Type A Internal Tooth Lock Washers	B18.21.1-1999
Type B Internal Tooth Lock Washers	B18.21.1-1999
Type A External Tooth Lock Washers	B18.21.1-1999
Type B External Tooth Lock Washers	B18.21.1-1999
Type A Countersunk External Tooth Lock Washers	B18.21.1-1999
Type B Countersunk External Tooth Lock Washers	B18.21.1-1999
Hardened Steel Circular Washers	B18.2.6-1996
Hardened Steel Circular Clipped Washers	B18.2.6-1996
Square Beveled Washers	B18.2.6-1996
Clipped Square Beveled Washers	B18.2.6-1996
Metric Washers	
Metric Plain Washer	B18.22M - 1981
Metric Helical Spring Lock Washer	B18.21.2M - 1999
Metric Tooth Lock Washer	B18.21.2M - 1999

Table A2f.2: Fastener – Tool mapping for Manual Handheld Fastening Tools .

(Note that fasteners highlighted in yellow are currently implemented in the library)

	Manual Handheld Fastening Tools								
Fastener Name	Double Head Box wrench	Double Head Ratcheting box wrench	Combination wrench	Adjustable wrench	Double Head Open end wrench	Double Head Flare nut wrench	Flat tip straight handle screwdriver	Cross-head ("Phillips") straight handle screw driver	Hex key
Inch Series Bolts									
Square Bolt	X	X	X	X	X	X			
Heavy Hex Structural Bolt	X	X	X	X	X	X			
Hex Bolt	X	X	X	X	X	X			
Heavy Hex Bolt	X	X	X	X	X	X			
Round Head Bolt	No Drive - Held by square slot in component - Tightened by installing nut on thread								
Round Head Square Neck Bolt	No Drive - Held by square slot in component - Tightened by installing nut on thread								
Round Head Short Square Neck Bolts	No Drive - Held by square slot in component - Tightened by installing nut on thread								
Round Head Fin Neck Bolt	No Drive - Held by fins on bolt and corresponding slots in Component - Tightened by installing nut on thread								
Round Head Ribbed Neck Bolt	No Drive - Held by ribs on bolt and corresponding slots in Component - Tightened by installing nut on thread								
Step Countersunk Square Neck Bolts	No Drive - Held by square slot in component - Tightened by installing nut on thread								
T-Head Bolts	No Drive - Held by T-shaped head resting in corresponding t-shaped slot in component - Tightened by installing nut on thread								
114-deg Countersunk Square Neck Bolts	No Drive - Held by square slot in component - Tightened by installing nut on thread								
Countersunk Bolts	No Drive - Held by friction between countersunk surface on bolt and countersink on part - Tightened by installing nut on thread								

Slotted Countersunk Bolts							X		
Metric Bolts									
Metric Hex Bolt	X	X	X	X	X	X			
Metric Heavy Hex Bolt	X	X	X	X	X	X			
Metric Heavy Hex Structural Bolt	X	X	X	X	X	X			
Metric Round Head Square Neck Bolt	No Drive - Held by Square Slot in Component - Tightened By Installing Nut on Thread								
Metric Round Head Short Square Neck Bolt	No Drive - Held by Square Slot in Component - Tightened By Installing Nut on Thread								
Inch Series Screws									
Heavy Hex Screws	X	X	X	X	X	X			
Hex Cap Screws	X	X	X	X	X	X			
Hex Flange Screws	X	X	X	X	X	X			
100-Degree Flat Countersunk Head Machine Screws	No Drive - Held by friction between countersunk surface on bolt and countersink on part - Tightened by installing nut on thread								
Slotted Flat Countersunk Head Machine Screws							X		
Slotted 100-Degree Flat Countersunk Head Machine Screws							X		
Slotted Close Tolerance 100-Degree Flat Countersunk Head Machine Screws							X		
Slotted Undercut 82-deg Flat Countersunk Head Machine Screws							X		
Plain Hex Washer Head Machine Screws	X	X	X	X	X	X			
Slotted Hex Washer Head Machine Screws	X	X	X	X	X	X	X		
Slotted Truss Head Machine Screw							X		
Slotted Hex Head Machine Screw	X	X	X	X	X	X	X		
Hex Head Machine Screw	X	X	X	X	X	X			
Slotted Pan Head Machine Screws							X		
Slotted Fillister Head Machine Screws							X		
Slotted Drilled Fillister Head Machine Screws							X		
Slotted Oval Countersunk Head Machine Screws							X		
Slotted Binding Head Machine Screws							X		
Slotted Undercut Oval Countersunk Head Machine Screws							X		

Slotted Round Head Machine Screws							X		
Metric screws									
Metric Hex Cap Screw	X	X	X	X	X	X			
Metric Formed Hex Screw	X	X	X	X	X	X			
Metric Heavy Hex Screw	X	X	X	X	X	X			
Metric Heavy Hex Flange Screw	X	X	X	X	X	X			
Metric Hex Flange Screw	X	X	X	X	X	X			
Metric machine screws									
Type I Cross Recessed Flat Countersunk Head Metric Machine Screw								X	
Type Ia Cross Recessed Flat Countersunk Head Metric Machine Screw								X	
Type I Cross Recessed Oval Countersunk Head Metric Machine Screw								X	
Type Ia Cross Recessed Oval Countersunk Head Metric Machine Screw								X	
Type I Cross Recessed Pan Head Metric Machine Screw								X	
Type Ia Cross Recessed Pan Head Metric Machine Screw								X	
Slotted Flat Countersunk Head Metric Machine Screw							X		
Slotted Oval Countersunk Head Metric Machine Screw							X		
Slotted Pan Head Metric Machine Screw							X		
Hex Head Metric Machine Screw	X	X	X	X	X	X			
Hex Flange Head Metric Machine Screw	X	X	X	X	X	X			
Square Recessed Flat Countersunk Head Metric Machine Screw	**No tools currently implemented in the library to install this fastener**								
Square Recessed Oval Countersunk Head Metric Machine Screw	**No tools currently implemented in the library to install this fastener**								
Square Recessed Pan Head Metric Machine Screw	**No tools currently implemented in the library to install this fastener**								
Inch Series Cap, Shoulder, and Set Screws									
Slotted Flat Countersunk Head Cap Screws							X		
Slotted Round Head Cap Screws							X		
Slotted Fillister Head Cap Screws							X		
Socket Head Cap Screws									X
Spline Socket Head Cap Screws	**No tools currently implemented in the library to install this fastener**								

Hexagon Socket Flat Countersunk Head Cap Screws									X
Spline Socket Flat Countersunk Head Cap Screws	**No tools currently implemented in the library to install this fastener**								
Hexagon Socket Button Head Cap Screws									X
Spline Socket Button Head Cap Screws	**No tools currently implemented in the library to install this fastener**								
Socket Head Shoulder Screws									X
Slotted Headless Set Screws									
Hexagon Socket Set Screw									X
Spline Socket Set Screw	**No tools currently implemented in the library to install this fastener**								
Square Head Set Screws	X	X	X	X	X	X			
Metric Cap and Shoulder Screws									
Metric Socket Head Cap Screw									X
Metric Socket Head Shoulder Screw									X
Metric Flat Head Countersunk Socket Cap Screw									X
Metric Socket Head Cap Screw, Spline Drive									
Metric Button Head Cap Screw									X
Inch Series Nuts									
Hex Nut	X	X	X	X	X	X			
Hex Jam Nut	X	X	X	X	X	X			
Heavy Hex Nut	X	X	X	X	X	X			
Heavy Hex Jam Nut	X	X	X	X	X	X			
Hex Flat Nut	X	X	X	X	X	X			
Hex Flat Jam Nut	X	X	X	X	X	X			
Heavy Hex Flat Nut	X	X	X	X	X	X			
Heavy Hex Flat Jam Nut	X	X	X	X	X	X			
Hex Slotted Nut	X	X	X	X	X	X			
Heavy Hex Slotted Nut	X	X	X	X	X	X			
Hex Thick Slotted Nut	X	X	X	X	X	X			
Square Nut	X	X	X	X	X	X			

Heavy Square Nut	X	X	X	X	X	X			
Hex Thick Nut	X	X	X	X	X	X			
Hex High Nut	X	X	X	X	X	X			
Hex Slotted High Nut	X	X	X	X	X	X			
Metric Nuts									
Metric Slotted Hex Nut	X	X	X	X	X	X			
Metric Hex Flange Nut	X	X	X	X	X	X			
Prevailing-Torque Metric Hex Flange Nut	X	X	X	X	X	X			
Prevailing-Torque Metric Hex Nut	X	X	X	X	X	X			
Metric Hex Jam Nut	X	X	X	X	X	X			
Metric Heavy Hex Nut	X	X	X	X	X	X			
Inch Series Washers									
Type A Plain Washers	**Installed by hand**								
Type B Plain Washers	**Installed by hand**								
High Collar Helical Spring Lock Washers	**Installed by hand**								
Helical Spring Lock Washers	**Installed by hand**								
Type A Internal-External Tooth Lock Washers	**Installed by hand**								
Type B Internal-External Tooth Lock Washers	**Installed by hand**								
Type A Internal Tooth Lock Washers	**Installed by hand**								
Type B Internal Tooth Lock Washers	**Installed by hand**								
Type A External Tooth Lock Washers	**Installed by hand**								
Type B External Tooth Lock Washers	**Installed by hand**								
Type A Countersunk External Tooth Lock Washers	**Installed by hand**								
Type B Countersunk External Tooth Lock Washers	**Installed by hand**								
Hardened Steel Circular Washers	**Installed by hand**								
Hardened Steel Circular Clipped Washers	**Installed by hand**								
Square Beveled Washers	**Installed by hand**								
Clipped Square Beveled Washers	**Installed by hand**								

Metric Washers									
Metric Plain Washer	**Installed by hand**								
Metric Helical Spring Lock Washer	**Installed by hand**								
Metric Tooth Lock Washer	**Installed by hand**								

Table A2f.3: Fastener – Tool mapping for Fastening Tools.

(Note that fasteners highlighted in yellow are currently implemented in the library)

	Fastening Tools						
Fastener Name	**Socket Wrench**	**Flat tip screwdriver socket bit**	**Cross-head screw driver socket bit**	**Hex Socket Bit**	**Flat Tip screwdriver Bit**	**Cross-head screwdriver bit**	**Hex bit**
Inch Series Bolts							
Square Bolt	X						
Heavy Hex Structural Bolt	X						
Hex Bolt	X						
Heavy Hex Bolt	X						
Round Head Bolt	No Drive - Held by square slot in component - Tightened by installing nut on thread						
Round Head Square Neck Bolt	No Drive - Held by square slot in component - Tightened by installing nut on thread						
Round Head Short Square Neck Bolts	No Drive - Held by square slot in component - Tightened by installing nut on thread						
Round Head Fin Neck Bolt	No Drive - Held by fins on bolt and corresponding slots in Component - Tightened by installing nut on thread						
Round Head Ribbed Neck Bolt	No Drive - Held by ribs on bolt and corresponding slots in Component - Tightened by installing nut on thread						

Step Countersunk Square Neck Bolts	No Drive - Held by square slot in component - Tightened by installing nut on thread						
T-Head Bolts	No Drive - Held by T-shaped head resting in corresponding t-shaped slot in component - Tightened by installing nut on thread						
114-deg Countersunk Square Neck Bolts	No Drive - Held by square slot in component - Tightened by installing nut on thread						
Countersunk Bolts	No Drive - Held by friction between countersunk surface on bolt and countersink on part - Tightened by installing nut on thread						
Slotted Countersunk Bolts		X			X		
Metric Bolts							
Metric Hex Bolt	X						
Metric Heavy Hex Bolt	X						
Metric Heavy Hex Structural Bolt	X						
Metric Round Head Square Neck Bolt							
Metric Round Head Short Square Neck Bolt							
Inch Series Screws							
Heavy Hex Screws	X						
Hex Cap Screws	X						
Hex Flange Screws	X						
100-Degree Flat Countersunk Head Machine Screws							
Slotted Flat Countersunk Head Machine Screws		X			X		
Slotted 100-Degree Flat Countersunk Head Machine Screws		X			X		
Slotted Close Tolerance 100-Degree Flat Countersunk Head Machine Screws		X			X		
Slotted Undercut 82-deg Flat Countersunk Head Machine Screws		X			X		
Plain Hex Washer Head Machine Screws	X						
Slotted Hex Washer Head Machine Screws	X	X			X		
Slotted Truss Head Machine Screw		X			X		
Slotted Hex Head Machine Screw	X	X			X		
Hex Head Machine Screw	X						
Slotted Pan Head Machine Screws		X			X		
Slotted Fillister Head Machine Screws		X			X		

Slotted Drilled Fillister Head Machine Screws		X			X		
Slotted Oval Countersunk Head Machine Screws		X			X		
Slotted Binding Head Machine Screws		X			X		
Slotted Undercut Oval Countersunk Head Machine Screws		X			X		
Slotted Round Head Machine Screws		X			X		
Metric screws							
Metric Hex Cap Screw	X						
Metric Formed Hex Screw	X						
Metric Heavy Hex Screw	X						
Metric Heavy Hex Flange Screw	X						
Metric Hex Flange Screw	X						
Metric machine screws							
Type I Cross Recessed Flat Countersunk Head Metric Machine Screw			X			X	
Type Ia Cross Recessed Flat Countersunk Head Metric Machine Screw			X			X	
Type I Cross Recessed Oval Countersunk Head Metric Machine Screw			X			X	
Type Ia Cross Recessed Oval Countersunk Head Metric Machine Screw			X			X	
Type I Cross Recessed Pan Head Metric Machine Screw			X			X	
Type Ia Cross Recessed Pan Head Metric Machine Screw			X			X	
Slotted Flat Countersunk Head Metric Machine Screw		X			X		
Slotted Oval Countersunk Head Metric Machine Screw		X			X		
Slotted Pan Head Metric Machine Screw		X			X		
Hex Head Metric Machine Screw	X						
Hex Flange Head Metric Machine Screw	X						
Square Recessed Flat Countersunk Head Metric Machine Screw							
Square Recessed Oval Countersunk Head Metric Machine Screw							
Square Recessed Pan Head Metric Machine Screw							
Inch Series Cap, Shoulder, and Set Screws							
Slotted Flat Countersunk Head Cap Screws		X			X		

Slotted Round Head Cap Screws		X			X		
Slotted Fillister Head Cap Screws		X			X		
Socket Head Cap Screws				X			X
Spline Socket Head Cap Screws							
Hexagon Socket Flat Countersunk Head Cap Screws				X			X
Spline Socket Flat Countersunk Head Cap Screws							
Hexagon Socket Button Head Cap Screws				X			X
Spline Socket Button Head Cap Screws							
Socket Head Shoulder Screws				X			X
Slotted Headless Set Screws							
Hexagon Socket Set Screw				X			X
Spline Socket Set Screw							
Square Head Set Screws	X						
Metric Cap and Shoulder Screws							
Metric Socket Head Cap Screw				X			X
Metric Socket Head Shoulder Screw				X			X
Metric Flat Head Countersunk Socket Cap Screw				X			X
Metric Socket Head Cap Screw, Spline Drive							
Metric Button Head Cap Screw				X			X
Inch Series Nuts							
Hex Nut	X						
Hex Jam Nut	X						
Heavy Hex Nut	X						
Heavy Hex Jam Nut	X						
Hex Flat Nut	X						
Hex Flat Jam Nut	X						
Heavy Hex Flat Nut	X						
Heavy Hex Flat Jam Nut	X						

Hex Slotted Nut	X						
Heavy Hex Slotted Nut	X						
Hex Thick Slotted Nut	X						
Square Nut	X						
Heavy Square Nut	X						
Hex Thick Nut	X						
Hex High Nut	X						
Hex Slotted High Nut	X						
Metric Nuts							
Metric Slotted Hex Nut	X						
Metric Hex Flange Nut	X						
Prevailing-Torque Metric Hex Flange Nut	X						
Prevailing-Torque Metric Hex Nut	X						
Metric Hex Jam Nut	X						
Metric Heavy Hex Nut	X						
Inch Series Washers							
Type A Plain Washers							
Type B Plain Washers							
High Collar Helical Spring Lock Washers							
Helical Spring Lock Washers							
Type A Internal-External Tooth Lock Washers							
Type B Internal-External Tooth Lock Washers							
Type A Internal Tooth Lock Washers							
Type B Internal Tooth Lock Washers							
Type A External Tooth Lock Washers							
Type B External Tooth Lock Washers							
Type A Countersunk External Tooth Lock Washers							
Type B Countersunk External Tooth Lock Washers							
Hardened Steel Circular Washers							

Hardened Steel Circular Clipped Washers							
Square Beveled Washers							
Clipped Square Beveled Washers							
Metric Washers							
Metric Plain Washer							
Metric Helical Spring Lock Washer							
Metric Tooth Lock Washer							

Table A2f.4: Assembly Process Definitions.		
Process or Term	**Definition**	**Source**
Mechanical Joint	Joint in which attachment of components in an assembly (or elements in a structure) is accomplished through the use of either an integral feature of the components or through the use of a supplemental device called a ‘‘fastener,’’ resulting in integral mechanical attachment and mechanical fastening, respectively.	Messler, R. W.. (2004). Joining of materials and structures: from pragmatic process to enabling technology. Amsterdam: Elsevier.
Tension loaded joint	Joint in which the primary loads are applied more or less parallel to the axes of the fasteners or attachment features.	Messler, R. W.. (2004). Joining of materials and structures: from pragmatic process to enabling technology. Amsterdam: Elsevier.
Shear loaded joint	Joint in which the primary loads are applied at right angles to the axes of the fasteners or attachment features.	Messler, R. W.. (2004). Joining of materials and structures: from pragmatic process to enabling technology. Amsterdam: Elsevier.
Bearing Type Shear Loaded Joint	Joint elements are held together by shear in the fastener (or integral feature) and the bearing force or stress in the joint elements created by the fastener (or integral feature). Fasteners or integral features act as pinning points to prevent movement of one joint element relative to the other, at least in translation (versus rotation). Examples are pins, nails, rivets and keys.	Messler, R. W.. (2004). Joining of materials and structures: from pragmatic process to enabling technology. Amsterdam: Elsevier.
Friction Type Shear Loaded Joint	Joint elements are held together by the clamping force imparted on them by the fastener and the resulting friction force that develops between the two joint elements. Typically only bolts can develop sufficient clamping forces to be properly used for such joints.	Messler, R. W.. (2004). Joining of materials and structures: from pragmatic process to enabling technology. Amsterdam: Elsevier.
Mechanical Fastener	mechanical device designed specifically to hold, join, couple, assemble, or maintain equilibrium of single or multiple components.	ASME B18.12-2001
Threaded Fastener	Any fastener such as a bolt, screw, nut, etc. that uses threads (which are a helical ramp around a cylindrical shaft or shank) to develop a clamping force between the fastener and a joint element or multiple joint elements through the principle of a screw.	Messler, R. W.. (2004). Joining of materials and structures: from pragmatic process to enabling technology. Amsterdam: Elsevier.
Bolt	An externally threaded product designed for insertion through holes in assemblies to mate with a nut and normally intended to be tightened or released by turning that nut.	ANSI/ASME B18.12-2001

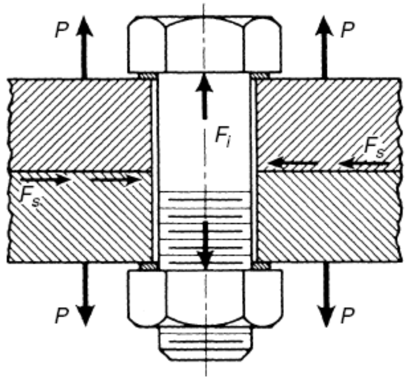
Button head bolt	Bolt with a low rounded top surface with a large flat bearing surface. Typically button head bolts have no driving features.	ANSI/ASME B18.12-2001
Round countersunk head bolt	Bolt with a circular head having a flat top surface and conical bearing surface. Typically round countersunk head bolts have no driving features.	ANSI/ASME B18.12-2001
T-Head bolt	Bolt with a rectangular shaped head, having a rounded top surface, flat sides, and a flat bearing surface. T-head bolts have no driving features.	ANSI/ASME B18.12-2001
Square countersunk head bolt	bolt having a square head with a flat top surface and pyramidal bearing surface.	ANSI/ASME B18.12-2001
Nut	A perforated block having an internal or female screw thread, designed to assemble with an external or male screw thread such as those on a bolt or other threaded part. Hexagon ("Hex") nuts have a hexagonal shape while Square nuts have a square shape.	ANSI/ASME B18.12-2001
Washer	A thin cylinder having a centrally located hole and is used with other fasteners as a spacer, a load distribution device, hardened seat, or to increase resistance to loosening in a fastened joint. Several different types of washers exist such as conical spring washers, plain washers, helical spring lock washers, etc. exist to perform varying functions based on the application.	ANSI/ASME B18.12-2001
Screw	Externally threaded fastener capable of being inserted into holes in assembledparts, of mating with a preformed internal thread or forming its own thread and ofbeing tightened or released by torquing the head.	Oberg, E., McCauley, C. J. (2004). Machinery's handbook: a reference book for the mechanical engineer, designer, manufacturing engineer, draftsman toolmaker and machinist. 27th ed. New York: Industrial Press.
Machine Screw	has a slotted, recessed, or wrenching head and threaded for assembly with a preformed external thread.	ANSI/ASME B18.12-2001
Tapping Screw	has a slotted, recessed, or wrenching head and is designed to form or cut a mating thread in one or more of the parts to be assembled.	ANSI/ASME B18.12-2001
Hexagon ("Hex") head bolt or screw	Bolt or screw with head with six sides.	ANSI/ASME B18.12-2001

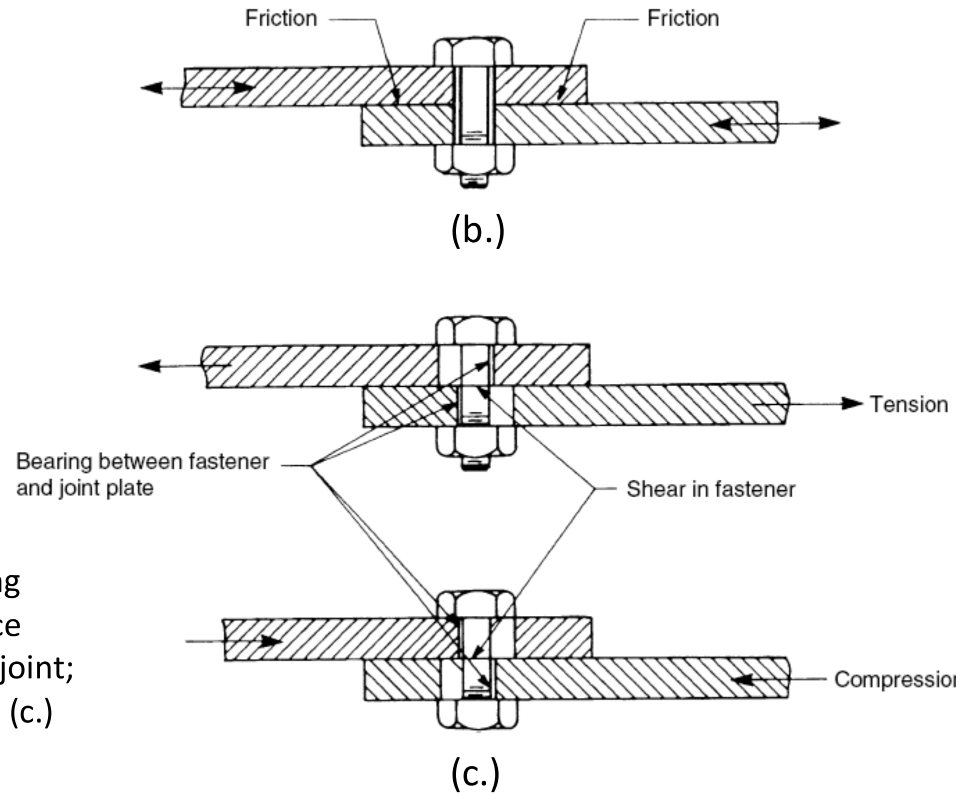
Square Head bolt or screw	Bolt or screw with head with four sides.	ANSI/ASME B18.12-2001
Slotted drive bolt or screw	Bolt or screw head having a slot centered across its top surface to facilitate driving.	ANSI/ASME B18.12-2001
Cross-recessed drive bolt or screw	Bolt or screw having a cross shaped recess to facilitate driving. 3 predominant cross recess types exist: (1.) Type I cross recess - recess with a large center opening, tapered wings, and a blunt bottom. (2.) Type IA cross - recess which is a recess with a large center opening, wide straight wings, and a blunt bottom. (3.) Type 2 cross recess - recess with two intersecting slots with parallel sides. The sides converge to a slightly truncated apex at the bottom.	Shigley, J. Edward. (2004). Standard handbook of machine design. 3rd ed. New York: McGraw-Hill.
Hexagon socket drive bolt or screw	Bolt or screw head with a hexagon socket formed in the center of the top surface to facilitate driving.	ANSI/ASME B18.12-2001
Spline socket drive bolt or screw	Bolt or screw head with a spline (formerly known as "fluted") socket formed in the center of the top surface to facilitate driving.	ANSI/ASME B18.12-2001
Square recess drive bolt or screw	Bolt or screw head with a square recess formed in the center of the top surface to facilitate driving.	
12-Point flange head screw	Screw that has a flat or indented top surface, 24 flats (double hex), with an integral formed circular collar connected to the base of the double hex by a conic section. It is sometimes called "double hexagon head."	ANSI/ASME B18.12-2001
12-spline head screw	has 12 splines centered at 30 deg increments around the outer circumference of the head and are parallel to the axis of the screw or bolt.	ANSI/ASME B18.12-2001
Threaded Stud	a cylindrical fastener, externally threaded on either one or both ends or over its entire length, designed for insertion through holes in assembled parts to either mate with a nut or into a threaded hole or into a hole to form its own thread.	ANSI/ASME B18.12-2001
Collar Stud	Stud threaded on one end having a collar of a diameter larger than the thread, and a retaining ring groove used to carry gears, cam rolls, and rocker levers.	ANSI/ASME B18.12-2001
Double end stud	Stud that has equal length threads on each end to accommodate a nut	ANSI/ASME B18.12-2001
Interference-thread double end stud (tapened stud)	Similar to double-end studs, except that one end has a particular thread type for installation into a tapped hole while the other end has a thread to accommodate a nut. Accordingly the stud is designed to be installed into a tapped hole.	ANSI/ASME B18.12-2001

Continuous thread stud	threaded from end to end and is often used for flange bolting with two nuts applied.	ANSI/ASME B18.12-2001
Projection weld stud	externally threaded component with round head of varied configuration having one or more integrally formed projections under or on top of the head suitable for resistance welding to a joint surface.	ANSI/ASME B18.12-2001
Wheel stud	a threaded stud consisting of a round head with serrations under the head for attaching the stud in place. Used for attaching wheels in the transportation industry.	ANSI/ASME B18.12-2001
Nominal size of a nut	Designation used for the purpose of general identification of a nut. E.g. "1/4 inch" nut. Nominal size corresponds to the basic major diameter of the threaded portion.	Oberg, E., McCauley, C. J. (2004). Machinery's handbook: a reference book for the mechanical engineer, designer, manufacturing engineer, draftsman toolmaker and machinist. 27th ed. New York: Industrial Press.
Nominal size of bolt or screw	Designation used for the purpose of general identification of a bolt or screw. E.g. "1/4 inch" bolt. Nominal size corresponds to the nominal outside diameter of the bolt or screw.	Oberg, E., McCauley, C. J. (2004). Machinery's handbook: a reference book for the mechanical engineer, designer, manufacturing engineer, draftsman toolmaker and machinist. 27th ed. New York: Industrial Press.
Nominal size of a washer	Designation used for the purpose of general identification of a washer. E.g. "1/4 inch" washer. Nominal size corresponds to the nominal size of the corresponding bolt or screw with which the washer is intended to be used. E.g. a 1/4" washer would be used with a 1/4" bolt.	Oberg, E., McCauley, C. J. (2004). Machinery's handbook: a reference book for the mechanical engineer, designer, manufacturing engineer, draftsman toolmaker and machinist. 27th ed. New York: Industrial Press.
Standard bolt/screw designation	Designation used for the purpose of identifying a screw or bolt. Bolts and screws should be designated by the following data, typically in the sequence shown: nominal size; thread specification; nominal length; drive type (slotted, type 1a cross head, spline, etc.), head style (hex, round, ball, etc.); fastener type (bolt, cap screw, machine screw, etc.); material, including specification, where necessary; and protective finish, if required. Example: 1⁄2-13 × 3 Round Head Square Neck Bolt, Steel, Zinc plated.	Oberg, E., McCauley, C. J. (2004). Machinery's handbook: a reference book for the mechanical engineer, designer, manufacturing engineer, draftsman toolmaker and machinist. 27th ed. New York: Industrial Press. ; ANSI/ASME B18.12-2001

Joint efficiency	measure of the effectiveness of the joint compared to the rest of the structure for carrying the design or service loads, and is defined by: = joint stress / [stress in structure x 100%]	Messler, R. W.. (2004). Joining of materials and structures: from pragmatic process to enabling technology. Amsterdam: Elsevier.
Unthreaded Fasteners		
Rivet	A headed and unthreaded metal fastener of malleable material used to join parts of structures and machines by inserting the shank through the aligned holes in each piece and forming a head on the headless end by upsetting.	ANSI/ASME B18.12-2001
Blind Rivet	A blind rivet is a fastener that has a self-contained mechanical or other feature that permits the formation of an upset on the blind end of the rivet and expansion of the rivet shank during rivet setting to join the component parts of an assembly.	ANSI/ASME B18.12-2001
Upsetting Rivet	Rivets that are plastically deformed to create at least the foot on a headed shank and sometimes both a head and a foot or two heads to lock or set the rivet in place. Upsetting rivets are divided into two major categories - 1.) solid, and 2.) tubular.	Messler, R. W.. (2004). Joining of materials and structures: from pragmatic process to enabling technology. Amsterdam: Elsevier.
Tubular upsetting rivet	a small rivet having a coaxial cylindrical or tapered hole in the headless end. It is commonly furnished with a countersunk, flat, oval, or truss head.	ANSI/ASME B18.12-2001
Integral Mechanical Attachment	Interference force(s) and resulting interlocking between two components is (are) provided by some natural, designed-in, or processed-in geometric feature of the parts or elements themselves, integral mechanical attachments are said to be involved.	Messler, R. W.. (2004). Joining of materials and structures: from pragmatic process to enabling technology. Amsterdam: Elsevier.
Crimps	Crimping is a process in which an outer piece is crushed, squeezed, or otherwise plastically deformed around another to prevent subsequent relative movement between the two.	Messler, R. W. (2006). Integral Mechanical Attachment: A Resurgence of the Oldest Method of Joining. Butterworth-Heinemann.
Stakes	Staking involves plastically deforming the metal of assembled parts in such a way that they cannot loosen or come apart under operating conditions. This deformation co-forms a protruding locking feature and a recessed locking feature in mating parts, simultaneously.	Messler, R. W. (2006). Integral Mechanical Attachment: A Resurgence of the Oldest Method of Joining. Butterworth-Heinemann.

Press fitting	One component (typically a pin or a key) is forced into a hole or slot that is too small to accept it without being deformed, creating interference. This interference results in very tight gripping due to the frictional forces developed by the elastic component of the force needed to deform the hole or slot to accept the pin or the key.	Messler, R. W. (2006). Integral Mechanical Attachment: A Resurgence of the Oldest Method of Joining. Butterworth-Heinemann.
	Assembly Tools	
Hinged Handle	Handle used for driving a socket in which the handle includes a steel hinged drive tang attached to a fork. The hinged drive tang shall be suitable for operation at an angle within a range of 90 deg in either direction from the longitudinal axis of the handle.	ANSI/ASME B107.10-2005
Reversible Ratchet Handle	Handle used for driving a socket that has either a gear head or clutch type and includes a head for housing a ratchet mechanism, and a drive tang. Ratcheting action is attained by means of a completely enclosed gear having hardened teeth engaging a hardened pawl or pawls, or by means of a completely enclosed clutch mechanism. Ratcheting action is reversible by annual movement of a shifting lever, button, or knob that permits ratcheting operation of the 2 drive tang in either direction of rotation.	ANSI/ASME B107.10-2005
Brace Type, Single Revolving Hand Grip Speeder Handle	Handle that has a square external tang at one end, and an attached rotatable metal handgrip or knob at the other end, used for driving a socket wrench.	ANSI/ASME B107.10-2005
Spin Type, Screwdriver Grip Speeder Handle	Handle that is shaped like a screw driver with a square external drive tang used for driving a socket wrench.	ANSI/ASME B107.10-2005
Sliding T Handle	Handle that consists of a socket holder and a steel rod. The socket holder has a transverse tool to accommodate the rod and forms a “T“ or “L“ handle tool.	ANSI/ASME B107.10-2005





Features Produced by Mechanical Joining Processes: (a.) Tension loaded (with force “P”) and shear-loaded (with force “Fs”) joint; (b.) friction type shear loaded joint; and (c.) bearing type shear loaded joint.

Pictures Courtesy of: Messler, R. W.. (2004). Joining of Materials and Structures: from pragmatic process to enabling technology. Amsterdam: Elsevier.

Figure A2f.3. Illustration of each type of feature (joint) produced by mechanical joining processes.

Table A2f.2. Mapping of features (joints) produced by common mechanical joining processes.

	Mechanical Fastening			Integral Mechanical Attachment		
	Threaded Fasteners	**Unthreaded Fasteners**		**Rigid Attachment Features**	**Elastic Attachment Features**	**Plastic Attachment Features**
Feature(s) Produced	**Installation of Threaded Fasteners**	**Installation of Rivets**	**Installation of Pins**	**Ball and Socket Snaps**	**Press Fits**	**Crimps**
Bearing Type Shear Loaded Joint	X	X	X	X	X [2]	X [2]
Friction Type Shear Loaded Joint	X	X [1]				
Tension Loaded Joint	X			X [2]	X [2]	X [2]

Notes:

1. Only some riveting processes can produce high enough compressive loads to create a friction type shear loaded joint.
2. Process produces the given type of joint but the joint can only support limited loads in the specified direction.

Table A2f.3 Mapping of mechanical joining processes to the material types for which each can be used.

	Mechanical Fastening			Integral Mechanical Attachment		
	Threaded Fasteners	Unthreaded Fasteners		Rigid Attachment Features	Elastic Attachment Features	Plastic Attachment Features
Materials Processed	**Installation of Threaded Fasteners**	**Installation of Rivets**	**Installation of Pins**	**Ball and Socket Snaps**	**Press Fits**	**Crimps**
Metals						
Ductile Metals[3]	X	X	X	X	X	X
Brittle Metals[3]	X	X	X	-	-	-
Ceramics	X[1]	-	-	-	-	-
Glass	X[1]	-	-	-	-	-
Plastics						
Thermoplastics	X[2]	X[2]	X[2]	X	?	X
Thermosets	X[2]	X[2]	X[2]	X	?	-
Elastomers	X	X	-	-	-	-
Composites						
Fiber Reinforced Plastics	X[2]	X[2]	X[2]	?	?	?
Metal Matrix Composites	X	X	X	?	?	-
Ceramic Matrix Composites	-	-	-	-	-	-

Key:

"X" = Feasible and examples known to exist

"?" = Feasibility likely but no known examples

"-" = infeasible

Notes:

1. Oversized washers, sleeves, and slotted hole approaches must be used to aovid stress concentration and subsequent cracking of the glass or ceramic.

2. Bolts, screws, and nuts with large head and sleeves and/or washers should be used with threaded fasteners; and large rivet heads when riveting to minimize stress concentrations.

3. Ductile metals are loosely defined as metals that can be plastically deformed by a reasonable means; brittle metals cannot be plastically deformed at a practical temperature.

(note: further future work will clearly define (using specific ductility characteristics) the ranges for "ductile" and "brittle" materials.

Source: Information derived from:

1.) Messler, R. W. (2006). Integral Mechanical Attachment: A Resurgence of the Oldest Method of Joining. Butterworth-Heinemann.

2.) Messler, R. W.. (2004). Joining of materials and structures: from pragmatic process to enabling technology. Amsterdam: Elsevier.

Table A2f.4. Mapping of common component mating area shapes to common mechanical joining processes.

<u>Important Note:</u> Components of any shape can be joined together using mechanical fastening processes. However, there will be constraints on the shapes of the mating areas (mating surfaces where the fastener is installed or where the integral attachment is made) on two structural elements. The table below considers the shapes of the mating areas between two components, not the shape of the component itself. It is evident from the table that the use of fasteners allows almost any shape of mating area. The shape codes shown are based on Ashby's shape classification system.

Process	Shape Codes for Mating Areas of components	Notes/Supporting Examples
Installation of Threaded Fasteners	R0-R6; Possibly R7, depending on the actual shape.	Holes can be drilled and threaded in round section or flat end section, screws or threaded rods could be installed for joining to other components.
	B0-B6; B7	Flats on "Bar" shapes very amenable to becoming mating surfaces and subsequent fastener installation points.
	S0-S6; Possibly S7, depending on the actual shape. SS0 - SS6; Possibly SS7, depending on the actual shape.	Flats on "Section" shapes very amenable to becoming mating surfaces and subsequent fastener installation points.
	T0 - T6; Possibly T7, depending on the actual shape.	Holes can be drilled and threaded in round section , set screws could be installed for inserting and fastening to solid rod, screws or threaded rods could be installed externally for joining to other components.
	F0 - F7	As mentioned above, flats provide a good mating surface and area for fasteners to be installed.
	Sp1, Sp6;	Holes can be drilled and threaded in the sperical section and a mating component with a matching curvature could be attached with a screw. Threaded rods could be installed for joining to other components as well.
	U2-U4; Possibly U7, depending on the actual shape of the mating area.	Flat surfaces of undercuts serve as ideal areas for mating and subsequent joining with threaded fasteners.

Installation of Rivets	R0-R6; Possibly R7, depending on the actual shape	Holes can be drilled and rivets installed on round sections or flat sections of round parts.
	B0-B6; B7	Flats on "Bar" shapes very amenable to becoming mating surfaces and subsequent rivet installation points.
	S0-S6; Possibly S7, depending on the actual shape. SS0 - SS6; Possibly SS7, depending on the actual shape.	Flats on "Section" shapes very amenable to becoming mating surfaces and subsequent rivet installation points.
	T0 - T6; Possibly T7, depending on the actual shape.	Holes can be drilled in round section, rivets can be installed.
	F0 - F7	Flats provide ideal mating surface and area for rivets to be installed.
	Sp1, Sp6;	Holes can be drilled in spherical section and a mating component with a matching curvature could be attached with a rivet.
	U2-U4; Possibly U7, depending on the actual shape of the mating area.	Flat surfaces of undercuts serve as ideal areas for mating and subsequent joining with rivets.

Installation of Pins	R0-R6; Possibly R7, depending on the actual shape	Holes can be drilled and pins installed on round sections or flat sections of round parts.
	B0-B6; B7	Flats on "Bar" shapes very amenable to becoming mating surfaces and subsequent pin installation points.
	S0-S6; Possibly S7, depending on the actual shape. SS0 - SS6; Possibly SS7, depending on the actual shape.	Flats on "Section" shapes very amenable to becoming mating surfaces and subsequent pin installation points.
	T0 - T6; Possibly T7, depending on the actual shape of the part.	Holes can be drilled in round section, rivets can be installed.
	F0 - F7	Flats provide ideal mating surface and area for pins to be installed.
	Sp1, Sp6;	Holes can be drilled in the spherical section and a mating component with a matching curvature could be attached with a pin.

	U2-U4; Possibly U7, depending on the actual shape of the mating area.	Flat surfaces of undercuts serve as ideal areas for mating and subsequent joining with pins.

Ball and Socket Snaps	SS7	"Socket" portion of ball and socket will be a semi-closed spherical section
	Sp1, Sp6;	By the definition of ball and socket type joints, the "ball" is a sphere that is snapped into a spherical-shaped socket.

Press Fits	R0-R6; Possibly R7, depending on the actual shape	Press fits are most commonly used with round solid parts (e.g. shafts) pressed into round hollow parts (e.g. bushings).
	T0 - T6; Possibly T7, depending on the actual shape of the part.	Following the above, round parts are pressed into tubular (round, hollow) parts such as bushings.

Crimps	R1, R7	Crimps are most commonly used for joining electrical wire with electrical terminals. Consequently, round solid parts represent wires as in shape R1, or strands of smaller wire wrapped into a round/cylindrical shape (R7).
	S0, S2, S3; SS0, Possibly S7 or SS7, depending on actual shape.	"female" portion of crimp.
	T0 - T4; T6; Possibly T7, depending on actual shape.	"female" portion of crimp could be all of these. Male portion could be T0-T4, T6, possibly T7, depending on actual shape.
	F1, F4	"female" portion of crimp.

Table A2f.5. Values of estimated RPM for several machines and tools included in the M-library.

Machine type	Estimated RPM (to be input in the "max speed" attribute at the instance level)
Manual Handheld Tools	
Adjustable wrench	15
Double Head Box wrench	15
Combination wrench	15
Cross-head ("Phillips") straight handle screw driver	60
Hex key	15
Double Head Flare nut wrench	15
Flat tip straight handle screwdriver	60
Double head open end wrench	15
Double head ratcheting box wrench	30
Manual Handheld Machines	
Hinged Handle	15
Reversible ratchet handle	30
Deflecting Beam Indicating Torque Wrench	15
Rigid Housing Indicating Torque Wrench	15
Indicating Screwdriver Torque Wrench	60
Ratcheting graduated setting torque wrench	30
Non-ratcheting graduated setting torque wrench	15
interchangeable head connection graduated setting torque wrench	15
flexible ratchet head graduated setting torque wrench	30
Ratcheting non-graduated setting torque wrench	30

Non-ratcheting non-graduated setting torque wrench	15
interchangeable head connection non-graduated setting torque wrench	15
flexible ratchet head non-graduated setting torque wrench	30
graduated screwdriver grip limiting torque wrench with square drive	60
graduated screwdriver grip limiting torque wrenchwith internal hex drive	60
non-graduated screwdriver grip limiting torque wrench with square drive	60
non-graduated screwdriver grip limiting torque wrench with internal hex drive	60
Non-ratcheting T-Handle Grip limiting torque wrench	15
Ratcheting T-Handle Grip limiting torque wrench	30
Brace Type, Single Revolving Hand Grip Speeder Handle	120
Spin Type, Screwdriver Grip Speeder Handle	60
Sliding T-Handle	15
Multi-Bit Screwdriver/Nut Driver Handle	60
Handheld Pneumatic and Power Machines	
Pneumatic ratchet wrench	max. speed attribute to be entered for each instance
Electric ratchet wrench	max. speed attribute to be entered for each instance
Pistol Grip Pneumatic impact wrench	max. speed attribute to be entered for each instance
Electric impact wrench	max. speed attribute to be entered for each instance
Electric screwdriver	max. speed attribute to be entered for each instance
Pistol Grip Pneumatic screwdriver	max. speed attribute to be entered for each instance

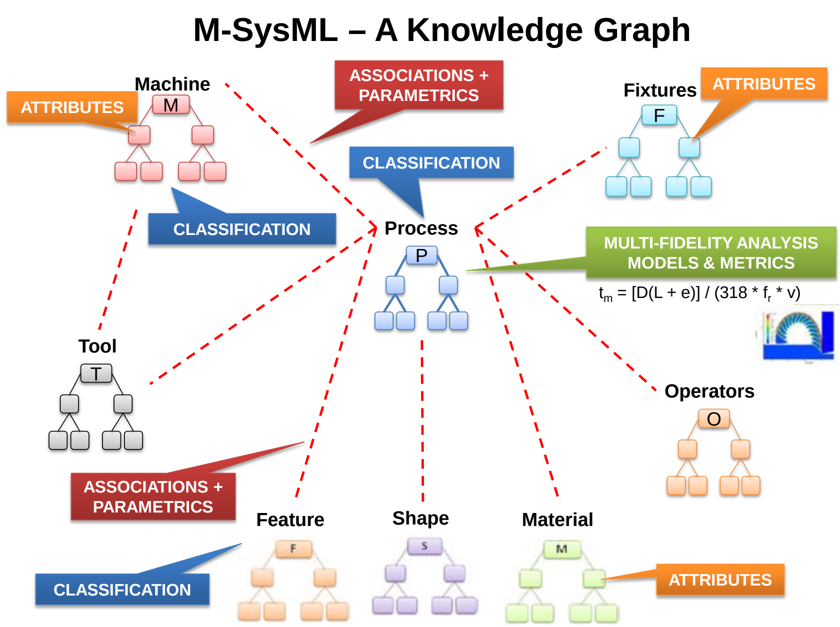
APPENDIX 4 (Task 3A M-Library Query Approach)

Fundamental Approach

1) M-Library is a graph at the backend.

2) The structure of the graph is conformant to the object-oriented M-SysML model that provides a unified ontology for manufacturing processes and related concepts, such as machines, tools, fixtures, operators, facilities, and other auxiliary resources. The M-SysML model contains: (a) detailed specializations of these concepts for different manufacturing domains, such as machining, assembly, welding, additive manufacturing, forming, and finishing; (b) relationships across these specializations for different manufacturing domains, e.g. specific machines, tools, fixtures, and operators for a given manufacturing process (e.g. Drilling or Gas Metal Arc Welding); and (c) properties of these specialized concepts (e.g. characteristics of a CNC Drilling Machine).

3) In the M-Library graph,
   a) Nodes are instances of concepts defined in M-SysML
   b) Nodes have two types of properties: primitive properties that hold primitives such as numbers, strings, and booleans; and complex properties that point to other nodes (concept instances).
   c) Edges are embodied as complex properties of nodes, specifically instances populating part/reference/shared properties of M-SysML concept instances.



4) M-Library query is a request to traverse the graph along certain edges (properties) starting with a concept. Therefore, a user of M-Library can:
   a) Access all primitive properties of a given concept instances
   b) Access all complex properties (graph edges) of a given concept instance
   c) Recursively access all properties (primitive/complex) of complex properties

***Note*: We are not encoding specific queries in the library. If the concept/property is modeled in the graph, a user will be able to traverse to it.**

5) In M-Library, most complex properties (edges) are bi-directional. So, M-Library users can start with any concept and work their way through the graph. For e.g. starting with a manufacturing process, users can access machines, and subsequently tools compatible with each machine. Or, starting with a machine, users can access processes that use that machine, tools compatible with the machine, operators that can operate the machine, and so on.

6) M-Library queries are of the following types:

   a) ***Q1**: Query primitive properties of a concept instance, e.g.*
      i) What is the weight of a given machine?
      ii) What working clearance is required for a fastening machine (e.g. wrench or screwdriver)?

   b) ***Q2**: Query complex properties of a concept instance, e.g.*
      i) What type of processes can be used to produce a given type of feature? Or conversely what types of features can a given process produce?
      ii) What types of machines are required for a given process? Or conversely what types of a process can be carried out on a given machine?

   c) ***Q3a**: Find concepts of a specific type in the M-Library*
   M-SysML contains 727 concepts (as of today). Users can search for all instances of a specific type of concept. For a listing of manufacturing process, machine and tool concepts, see the end of Appendix 3A.

   ***Q3b**: Find concepts of a specific type in the M-Library given one or more criteria*

   Select all *Fastening Machines* such that ALL (or ANY) of the criteria are satisfied

   Fastening Machine . length **>** 5 in

   Fastening Machine . working torque **>** 100 lbf-in

   Fastening Machine . applicable_for_fasteners **typeOf** Hex/Square Head Bolt with Hex/Square Head Nut

   Properties (primitive/complex) are accessible using the dot notation, same as we do for object oriented models. Criteria may be constructed from arbitrarily deep-nested properties (e.g. A.b.c.d). When specifying criteria, the following list of operators are currently supported:

Operator	Meaning
=	*equal to*
<	*less than*
>	*greater than*
<=	*less than or equal to*
>=	*greater than or equal to*
:= (typeOf)	*is type of*
exists in	*exists in the set*

d) Q4*: Compute the time and cost for unit processes*

7) M-Library will also contain executable time and cost models for unit processes. The models have been identified/developed by our team and in the process of being encoded and deployed in the library.

Example Queries Supported by M-Library

In this section, we list some representative M-Library queries. Since the library is a graph, if a property exists for a concept, it can be traversed. We recommend reviewers of this document to explore the M-SysML model for the complete dictionary of concepts and properties.

Given a manufacturing process type

Example queries of type Q1

For any manufacturing process:

1. What is the economic batch size of the process?
2. What is the max throughput of the process?

Specific manufacturing processes have additional primitive attributes beyond those inherited from a generic process. For e.g. if you select a welding process as a starting point, you can pose additional queries such as below.

1. What is the cross-sectional thickness (range) of the metal that can be welded using the process?
2. What types of welding joints can be created using the process?
3. In what types of positions can the welding process be performed?

All the manufacturing process types in M-SysML are listed at the end of Appendix 3A.

Example queries of type Q2

1. What types of features can be produced by the process?
2. What are the allowable materials for the process?
3. What types of machines and tools are used by the process?
4. What types of fixtures are required for the process?
5. What other auxiliary resources are required for the process?

Example queries of type Q3b

1. Select all manufacturing processes such that:
    a. they can produce a *through hole feature*
    b. in a *metal* workpiece

2. Select all manufacturing process such that:
    a. they can produce a *complex boundary feature*
    b. in a plastic workpiece
    c. with tolerance X
    d. with surface roughness Y

Example queries of type Q4

What is the time and cost to complete a process given:

- Input and output workpiece, and produced features
- Machine and tool used to carry out the process
- Operational parameters (e.g. cutting rate)
- Cost/time for using the machine and operator

The specific parameters in time/cost models are different for each process type. For e.g. the slide below shows a simple time and cost model (and a worked out example) for material removal processes.

Material Removal Processes

$$[MRR] = 1000 \times V_{m/min} \times f \times d$$

Ref: Parashar, B. S. Nagendra., and R. K. Mittal. *Elements of Manufacturing Processes*. New Delhi: Prentice-Hall of India, 2003. Print.

Additional user input for Turning, Parting, Drilling, Threading, Reaming, Boring:

- ❑ Initial workpiece volume, mm^3, $Vol_{initial}$
- ❑ Final workpiece volume, mm^3, Vol_{final}

Preset (library), but adjustable input (Turning, Parting, Drilling, Threading, Reaming, Boring) :

- ❑ Cutting Speed, m/min, *V*
- ❑ Feed rate, mm/rev, *f*
- ❑ Depth of cut per pass, mm, *d*

Example:

User inputs: Turning, Billing rate \$0.75/min, Cutting Tool Material = HSS, Ductile Cast Iron ASTM A536 65-45-12, $Vol_{final} - Vol_{initial} = 300mm^3$.

Preset (library), inputs: *d = 1 mm, f = 0.18* mm/rev*, and V* = 60 m/min.

Outputs:

[MRR] = [1000 mm/m 60 m/min * 0.18 mm * 1 mm] = 10800 mm³/min*
[Time] = [300 mm³] / [10800 mm³/min] = 0.03 min = 1.8 seconds
*[Cost] = [\$2.00/min] * [0.03 min] = \$0.06*
Recommended tool grade: S4, S5 (M2, M3)

Given a machine type

Example queries of type Q1

For any type of machine, a user can pose a query to get one or more of the following properties.

#	Name	Type
1	billing rate	$/hr
2	power rating - max current	A
3	weight	kg
4	control system	String
5	power rating - min frequency	Hz
6	dimension - width	mm
7	power rating - min voltage	V
8	purchase cost	$
9	power rating - min current	A
10	power rating - max frequency	Hz
11	communication ports	String
12	power rating - max voltage	V
13	power rating - phase	String
14	machine manufacturer	String
15	dimension - depth	mm
16	has CNC controller	Boolean
17	dimension - height	mm
18	max payload	kg
19	model id	String

Specific machines have additional properties beyond the generic ones listed above. For e.g. a user can query the following additional properties for a *CNC Lathe* machine.

#	Name	Type
1	spindle - nose type	String
2	spindle - max torque	N-m
3	center distance	mm
4	draw tube type	String
5	max machining length	mm
6	max feed rate - y axis	mm/min
7	max load on each axis	kg
8	number of turret stations	Integer
9	max feed rate - z axis	mm/min
10	chuck size	mm
11	max machining diameter	mm
12	max feed rate - x axis	mm/min
13	spindle - number of spindles	Integer

As another example, the table below lists additional properties for a *Machining Center*.

#	Name	Type
1	axis travel - c axis	deg
2	spindle - number of spindles	Integer
3	axis travel - a axis	deg
4	cutting fluid - through-tool capability	Boolean
5	number of pallets	Integer
6	pallet - size width	mm
7	automatic tool changer - max tool weight	kg
8	automatic tool changer - magazine capacity	Integer
9	spindle - outside diameter	mm
10	pallet - size depth	mm
11	automatic tool changer - max tool diameter	mm
12	spindle - max speed	rpm
13	spindle - through coolant	Boolean
14	accuracy - repeatability	mm
15	automatic tool changer - max tool length	mm
16	automatic tool changer - average tool change time	s
17	spindle - arbor type	String
18	spindle - max torque	N-m
19	max load on each axis	kg
20	coolant pressure	bar
21	worktable - max feed rate	mm/min
22	cutting fluid	String
23	degrees of freedom	Integer
24	worktable - min feed rate	mm/min
25	pallet - table load	kg
26	spindle - max distance to table	mm
27	axis travel - b axis	deg

All the manufacturing process types in M-SysML are listed at the end of Appendix 3A.

Example queries of type Q2

1. What types of processes can be performed on a given type of machine?
2. What types of tools can be installed on a given type of machine?
3. What types of operators can run/operate a given type of machine?
4. What facilities have a given type of machine in their equipment portfolio? *See* Facility *section for related queries*.

Example query of type Q3b

Select all machines:

a. that can be used for fastening a hex/square head bolt with hex/square head nut
b. that require clearance (perpendicular to the fastener) no more than *x* mm
c. that can apply a torque of *y* N-m to the fastener

Given a tool

Example queries of type Q1

For any type of tool, a user can pose a query to get one or more of the following properties.

#	Name	Type
1	max speed	m/s
2	working volume	Volume
3	weight	kg
4	degrees of freedom	Integer
5	min speed	m/s
6	price	$
7	resolution	mm
8	tool life	Years
9	positioning accuracy	Micrometer

Specific tools have additional properties beyond the generic ones listed above. For e.g. a user can query the following additional properties for a *Die*.

#	Name	Type
1	corner and fillet radii	mm
2	die closure/thickness tolerance	mm
3	draft angle	deg
4	finishing allowance	mm
5	length tolerance	mm
6	match/dismatch tolerance	mm
7	max rib height	mm
8	min section thickness	mm
9	parting line	String
10	width tolerance	mm

All the manufacturing process types in M-SysML are listed at the end of Appendix 3A.

Example queries of type Q2

1. On what types of machines can a given tool be installed?
2. What processes use a given type of tool?

Given a facility

Example queries of type Q2

1. What are the different *types* of machines, tools, and fixtures available at a given facility?
    a. How many of each type are available?
    b. What workstations and departments are they located at?
2. What are the departments and aisles (material handling systems) at a given facility?
3. What are the workstations at a given department?
4. What are the machines, fixtures, and tools at a given workstation?
5. Where in the facility is a given workstation located?

Given a fixture

Example queries of type Q1

For any type of fixture, a user can pose a query to get one or more of the following properties.

#	Name	Type
1	range of motion - v rotation	deg
2	range of motion - x translation	mm
3	clamping pressure	N/m2
4	part location accuracy	mm
5	range of motion - u rotation	deg
6	weight	kg
7	price	$
8	range of motion - w rotation	deg
9	range of motion - z translation	mm
10	size - length	mm
11	size - width	mm
12	range of motion - y translation	mm
13	size - height	mm

Specific types of fixtures have additional properties beyond the generic ones listed above. For e.g. a *Welding Positioner* has following additional properties that a user can query.

#	Name	Type
1	table diameter	mm
2	max table tilt	deg
3	max table rotation	deg
4	max table load	kg

Given an operator

Example queries of type Q1

For any operator, a user can pose a query to get one or more of the following properties.

#	Name	Type
1	age	Integer
2	height	Real
3	hourly rate	$
4	name	String
5	sex	String
6	speed	Parts/day
7	weight	Real
8	years of experience	Years

Example queries of type Q2

1. What types of machines can a given operator operate?
2. What are the different types of skills does an operator have?
3. What types of processes can be performed by an operator?

Types of manufacturing processes (flattened inheritance hierarchy) - 176

1. Abrasive Machining
2. Abrasive Water Jet Machining
3. Additive Manufacturing
4. Adhesive Bonding
5. Arc Welding
6. Ball End Milling
7. Bending
8. Bevel Cutting
9. Blanking
10. Boring
11. Brazing
12. Bulk Deformation
13. Burnishing
14. Casting
15. Chemical Removal
16. Closed-die Forging
17. Coating
18. Cogging
19. Coining
20. Continuous Fiber Thermoplastic Manufacturing

21. Continuous Fiber Thermoset Manufacturing
22. Deburring
23. Deep Drawing
24. Die Casting
25. Diffusion Bonding
26. Direct Drive Friction Welding
27. Drawing
28. Drilling
29. Edging
30. Electrical Discharge Machining (EDM)
31. Electrical Removal
32. Electro-Chemical Maching (ECM)
33. Electron Beam Machining
34. End Milling
35. Expendable Mold Casting
36. Extrusion
37. Face Milling
38. Facing
39. Fastening with 12-point Flange Head
40. Fastening with 12-point Spline Head
41. Fastening with Ball and Socket Snaps
42. Fastening with Blind Rivets
43. Fastening with Bolts and Nuts
44. Fastening with Cantilever Hooks and Catches
45. Fastening with Clutch Recessed Drive Screws
46. Fastening with Coller Stud
47. Fastening with Continuous Thread Stud
48. Fastening with Crimps
49. Fastening with Cross-Recessed Drive Scews
50. Fastening with Double End Stud
51. Fastening with Dovetail Joints
52. Fastening with Elastic Attachment Features
53. Fastening with Finger Snaps
54. Fastening with Hems
55. Fastening with Hex Head Screws
56. Fastening with Hex/Square Head Bolts with Hex/Square Head Nuts
57. Fastening with Hexagon Socket Drive Screws
58. Fastening with Integral Mechanical Attachments
59. Fastening with Interference Thread Double End Stud
60. Fastening with Mechanical Fasteners
61. Fastening with no-drive Bolts with Hex/Square Nuts
62. Fastening with Pins
63. Fastening with Plastic Attachment Features

64. Fastening with Pressure Fit Joint
65. Fastening with Projection Weld Stud
66. Fastening with Rigid Attachment Features
67. Fastening with Rivets
68. Fastening with Screws
69. Fastening with Slotted Drive Hex Head Bolts with Hex/Square Nuts
70. Fastening with Slotted Drive Screws
71. Fastening with Snap Fit Integral Attachments
72. Fastening with Spline Socket Drive Screws
73. Fastening with Square Recess Drive Screws
74. Fastening with Thermal Shrink Fits
75. Fastening with Threaded Fasteners
76. Fastening with Threaded Studs and Nuts
77. Fastening with Unthreaded Fasteners
78. Fastening with Upsetting Rivets
79. Fastening with Wheel Stud
80. Finishing
81. Flux Cored Arc Welding
82. Fly Cutting
83. Forging
84. Forming
85. Friction Stir Welding
86. Friction Welding
87. Fullering
88. Fused-Deposition Modeling
89. Gas Metal Arc Welding
90. Gas Tungsten Arc Welding
91. GMT Compression Molding
92. Grinding
93. Heading
94. Honing
95. Hubbing
96. Impression-die Forging
97. Incremental Forging
98. Inertia Friction Welding
99. Investment Casting
100. Isothermal Forging
101. Joining and Assembly
102. Lapping
103. Laser Beam Welding
104. Laser Cutting
105. Linear Friction Welding
106. Machining

107. Mechanical Fastening
108. Mechanical Removal
109. Milling
110. Multi-Point Cutting
111. Open-die Forging
112. Orbital Forging
113. Oxyacetylene Welding
114. Oxyfuel Gas Cutting
115. Oxyfuel Gas Welding
116. Parting
117. Permanent Mold Casting
118. Piercing
119. Plasma Arc Cutting
120. Plating
121. Polishing
122. Polymer and Composite Manufacturing
123. Powder Bed Fusion
124. Powder Bed Fusion - Metal
125. Powder Bed Fusion - Polymer
126. Powder Metallurgy
127. Powder Spray
128. Prepeg Lay-up
129. Punching
130. Radial Bending
131. Radial Friction Welding
132. Reaming
133. Reducing (Chips)
134. Resin Infusion
135. Resin Transfer Molding (RTM)
136. Resistance Spot Welding
137. Resistance Welding
138. Roll Bending
139. Roll Forging
140. Rolling
141. Sand Casting
142. Sawing
143. Separating (Shear)
144. Shearing
145. Sheet Forming
146. Shielded Metal Arc Welding
147. Short Fiber Thermoplastic Manufacturing
148. Short Fiber Thermoset Manufacturing
149. Single-Point Cutting

150. Sinker EDM
151. Skew Forging
152. SMC Compression Molding
153. Soldering
154. Solid State Welding
155. Spray-up
156. Stamping
157. Stereolithography
158. Straight-angle Bending
159. Structural Reactive Injection Molding (SRIM)
160. Stud Welding
161. Submerged Arc Welding
162. Surface Treating
163. Thermal Removal
164. Thermit Welding
165. Thermoforming
166. Thermoplastic Composites Manufacturing
167. Thermoplastic Injection Molding
168. Thermoset Composites Manufacturing
169. Threading
170. Tube Bending
171. Turning
172. Ultrasonic Consolidation
173. Ultrasonic Machining
174. Welding
175. Wet Lay-up
176. Wire EDM

Types of machines (flattened inheritance hierarchy) - 160

1. Additive Manufacturing Machine
2. Adjustable Wrench
3. Air-Lift Hammer
4. Arc Stud Welder
5. Arc Welder
6. Arc Welding Machine
7. Band Saw
8. Bending Brake
9. Board Hammer
10. Box Wrench
11. Brace Type, Single Revolving Hand Grip Speeder Handle with Socket Wrench
12. Brace Type, Single Revolving Hand Grip Speeder Handle with Socket Wrench / Bits

13. CD Stud Welder
14. Centerless Grinder
15. CNC Drilling and Tapping Machine
16. CNC Drilling and Tapping Machine with Drill Tool
17. CNC Drilling and Tapping Maching with Reaming Tool
18. CNC Lathe
19. CNC Lathe with Boring Tool
20. CNC Lathe with Drill Tool
21. CNC Lathe with Facing Tool
22. CNC Lathe with Parting Tool
23. CNC Lathe with Reaming Tool
24. CNC Lathe with Threading Tool
25. CNC Lathe with Turning Tool
26. Combination Wrench
27. Compression Machine
28. Compression Molding Machine
29. Cross-Head Straight Handle Screw Driver
30. Cylindical Grinder
31. Deep Drawing Machine
32. Direct Drive Friction Welder
33. Electric Impact Wrench
34. Electric Impact Wrench with Socket Wrench
35. Electric Ratchet Wrench
36. Electric Ratchet Wrench with Socket Wrench
37. Electric Screwdriver
38. Engine Lathe
39. Engine Lathe with Boring Tool
40. Engine Lathe with Drill Tool
41. Engine Lathe with Facing Tool
42. Engine Lathe with Parting Tool
43. Engine Lathe with Reaming Tool
44. Engine Lathe with Threading Tool
45. Engine Lathe with Turning Tool
46. Fastening Machine
47. FCAW Machine
48. Flare Nut Wrench
49. Flat Tip Straight Handle Screwdriver
50. Flux-Cored Welder
51. Forging Machine
52. Forging Press
53. Friction Stir Welder
54. Friction Welding Machine
55. Fused Deposition Modeling Machine

56. GMAW Machine
57. GTAW Machine
58. Hammer
59. Handheld Pneumatic and Power Tools
60. Helve and Trip Hammer
61. Hex Key
62. High-Energy-Rate Forging Machine
63. Hinged Handle with Socket Wrench
64. Hinged Handle with Socket Wrench / Bits
65. Hydraulic Press
66. Impacter
67. Inertia Friction Welder
68. Ink-Jet Printing
69. Laser Cutting Machine
70. Lathe
71. Linear Friction Welder
72. Machining Center
73. Machining Center with Boring Tool
74. Machining Center with Drill Tool
75. Machining Center with End Mill
76. Machining Center with Face Mill
77. Machining Center with Profile Mill
78. Machining Center with Reaming Tool
79. Machining Center with Threading Tool
80. Manual Drill Press
81. Manual Drill Press with Drill Tool
82. Manual Drill Press with Reaming Tool
83. Manual Hand Held Tools with Socket Wrenches / Bits
84. Manual Handheld Tools (without socket wrenches)
85. Manual Milling Machine
86. Manual Milling Machine with Boring Tool
87. Manual Milling Machine with Drill Tool
88. Manual Milling Machine with End Mill Tool
89. Manual Milling Machine with Face Mill Tool
90. Manual Milling Machine with Profile Mill Tool
91. Manual Milling Machine with Reaming Tool
92. Mechanical Forging Press
93. Metal Shear
94. MIG Welder
95. Multi-Bit Screwdriver Handle
96. Multi-Process Welder
97. OAW Machine
98. Open End Wrench

99. Pneumatic Impact Wrench
100. Pneumatic Impact Wrench with Socket Wrench
101. Pneumatic Ratchet Wrench
102. Pneumatic Ratchet Wrench with Socket Wrench
103. Powder Bed Fusion Machine
104. Powder Bed Fusion Machine (Metal)
105. Powder Bed Fusion Machine (Polymer)
106. Powder Spray Machine
107. Precision Grinding Machine
108. Punching Press
109. Radial Drill Machine
110. Radial Drill Machine with Drill Tool
111. Radial Drill Machine with Reaming Tool
112. Radial Friction Welder
113. Ratcheting Box Wrench
114. Reactive Injection Molding Machine
115. Reaming Machine
116. Resin Infusion Molding Machine
117. Resin Transfer Molding Machine
118. Resistance Welding Machine
119. Reversible Ratchet Handle with Socket Wrench
120. Reversible Ratchet Handle with Socket Wrench / Bits
121. Robot Spray-Up Machine
122. Robotic Arc Stud Welder
123. Robotic Arc Welder
124. Robotic CD Stud Welder
125. Robotic Direct Drive Friction Welder
126. Robotic Flux-Cored Welder
127. Robotic Friction Stir Welder
128. Robotic Inertia Friction Welder
129. Robotic Linear Friction Welder
130. Robotic MIG Welder
131. Robotic Radial Friction Welder
132. Robotic Spot Welder
133. Robotic Submerged Arc Welder
134. Robotic TIG Welder
135. RSW Machine
136. SAW Machine
137. Screw Press
138. Sliding T-Handle with Socket Wrench
139. Sliding T-Handle with Socket Wrench / Bits
140. SMAW Machine
141. Solid State Welding Machine

142. Spin Type Screwdriver Grip Speeder Handle with Socket Wrench
143. Spin Type Screwdriver Grip Speeder Handle with Socket Wrench / Bits
144. Spot Welder
145. Stamping Press
146. Steam Hammer
147. Stereolithography Machine
148. Submerged Arc Welder
149. Surface Grinder
150. Thermoforming Machine
151. Thermoplastic Injection Machine
152. TIG Welder
153. Torque Wrench with Socket Wrench
154. Torque Wrench with Socket Wrench / Bits
155. Tube Bender
156. Ultrasonic Consolidation Machine
157. Vertical Counterblow Hammer
158. Water Jet Machine
159. Welding Machine

Types of tools (flattened inheritance hierarchy) - 59

1. Acetylene Regulator
2. Automatic MIG Gun
3. Boring Tool
4. Closed Hard Mold
5. Closed Hard-Soft Mold
6. CNC Drilling and Tapping Machine Tool
7. Counterbore Tool
8. Countersink Tool
9. Cross Head Screw Driver Socket Bit
10. Cross-Head Screwdriver Bit
11. Cutoff Tool
12. Cutting Blade
13. Die
14. Drill
15. Drive Mechanism
16. Electrode Holder
17. End Mill
18. Engine Lathe Tool
19. Face Mill
20. Facing Tool
21. Fastening Machine Tool
22. Flat Tip Screwdriver Bit

23. Flat Tip Screwdriver Socket Bit
24. Flux Hopper
25. Flux-Cored Gun
26. Forging Roll
27. Forging Tool
28. Ground Clamp
29. Handheld MIG Gun
30. Hex Bit
31. Hex Bit Socket
32. Knurling Tool
33. MIG Gun
34. Milling Tool
35. Mold
36. Multi-Point Cutting Tool
37. Open FRP Mold
38. Open Metallic Mold
39. Oxyacetylene Welding Torch
40. Oxyen Regulator
41. Parting Tool
42. Profile Mill
43. Punch
44. Reamer
45. Single-Point Cutting Tool
46. Socket Wrench
47. Solid Single-Point Cutting Tool
48. Spool Gun
49. Spot Weld Gun
50. Submerged Arc Torch
51. Tap
52. Threading Tool
53. TIG Torch
54. Turning Tool
55. Welding Tool
56. Wire Feeder
57. Wrench/Bit Tool for Pneumatic Ratchet Wrench
58. Wrench/Bit Tool for Speeder Handle
59. Wrench/Bit Tool for Spin Type Screwdriver Grip Speeder Handle

Types of product features (flattened inheritance hierarchy) - 59

1. Assembly Feature
2. Back or Backing Weld
3. Bend

4. Bevel Groove Weld
5. Blind Bevel
6. Blind Complex Pocket
7. Blind Feature
8. Blind Hole
9. Blind Linear Pocket
10. Blind Pocket
11. Blind Revolute
12. Blind Screw Thread
13. Blind Slot
14. Boss
15. Boundary Through Feature
16. Boundary Through Feature - Complex
17. Boundary Through Feature - Linear
18. Chamfer
19. Complex Edge Feature
20. Corner Weld
21. Edge Feature
22. Edge Weld
23. Fillet
24. Fillet Weld
25. Flange Weld
26. Flare Bevel Groove Weld
27. Flare V Groove Weld
28. Groove Weld
29. Interior Through Feature
30. J Groove Weld
31. Negative Feature
32. Plug Weld
33. Positive Feature
34. Projection Weld
35. Radial Bend
36. Rib
37. Ring
38. Roll Bend
39. Scarf Groove Weld
40. Seam Weld
41. Slot Weld
42. Solid Body
43. Sphere
44. Spot Weld
45. Square Groove Weld
46. Step

47. Straight-angle Bend
48. Stud Weld
49. Surfacing Weld
50. Through Complex Boundary
51. Through Feature
52. Through Hole
53. Through Linear Boundry
54. Through Screw Thread
55. Tube Bend
56. U Groove Weld
57. V Groove Weld
58. Wall
59. Weld

Types of Fasteners (flattened inheritance hierarchy) – 36

1) 12 Point Flange Head
2) 12 Spline Head
3) Blind Revet
4) Bolt and Nut
5) Bolt with no drive, with Square or Hex Nut
6) Button Head Bolt with Square or Hex Nut
7) Clutch-Recessed Drive Screw
8) Collar Stud and Nut
9) Continuous Thread Stud and Nut
10) Cross-Recessed Drive Screw
11) Double End Stud and Nut
12) Eyelet and Grommet
13) Hex and Square Head Bolt with Hex or Square Nut
14) Hex Head Screw
15) Hexagon Socket Drive Screw
16) Interference-Thread Double End Stud
17) Key with Keyway
18) Nail, Brad, Tack
19) Pin
20) Projection Weld Stud and Nut
21) Retaining Ring or Clip
22) Rivet
23) Round Countersunk Head Bolt with Square or Hex Nut
24) Screw
25) Slotted Drive Hex Head Bolt with Hex or Square Nut
26) Slotted Drive Screw
27) Snap

28) Spline Socket Drive Screw
29) Square Countersunk Head Bolt with Square or Hex Nut
30) Square Recess Drive Screw
31) T-head Bolt with Square or Hex Nut
32) Threaded Fastener
33) Threaded Stud and Nut
34) Unthreaded Fastener
35) Upsetting Rivet
36) Wheel Stud and Nut

APPENDIX 5 (Task 3B META-iFAB Interactions)

META-iFAB Assembly Exercise & iFAB Interactions

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Purdue University

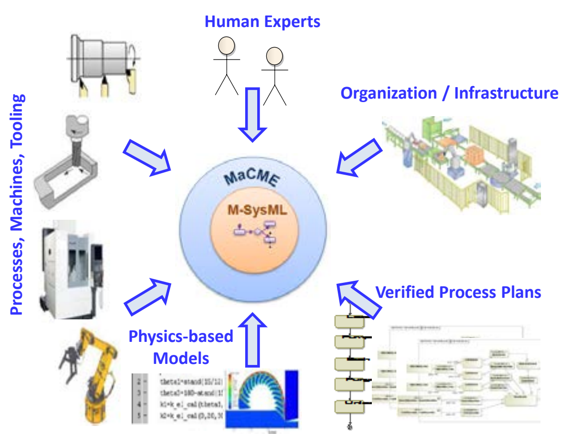
MANUFACTURING RESEARCH CENTER — Georgia Tech Research Institute — intercax — THIRD WAVE SYSTEMS

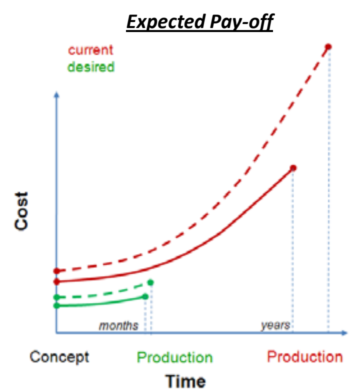
1

Overview

Objective: Develop digital library of multi-domain manufacturing process and machine models to support the rapid (re)configuration of a virtual foundry for fabricating a meta-encoded product design.

Multi-domain Manufacturing Capability Library (M-Library) and Modeling Environment

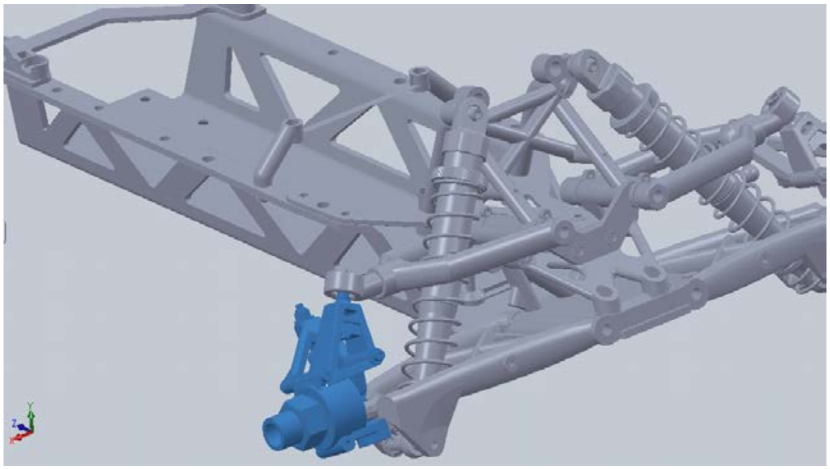




Current State-of-the-Art : Limited scope of domain knowledge; mostly empirical and/or heuristic (no physics-based models); non-standard characterization

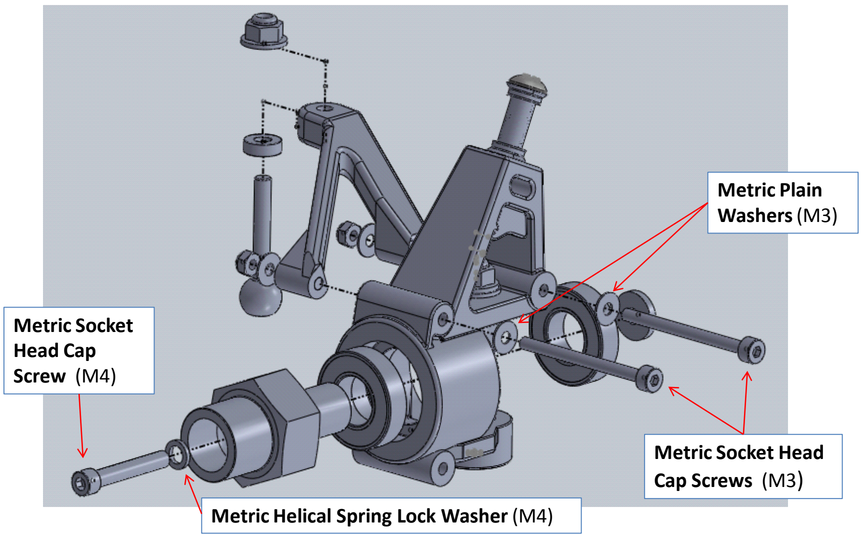
2

Part 1 : Assembly (Fastening) Queries
Front Hub Right Assembly



3

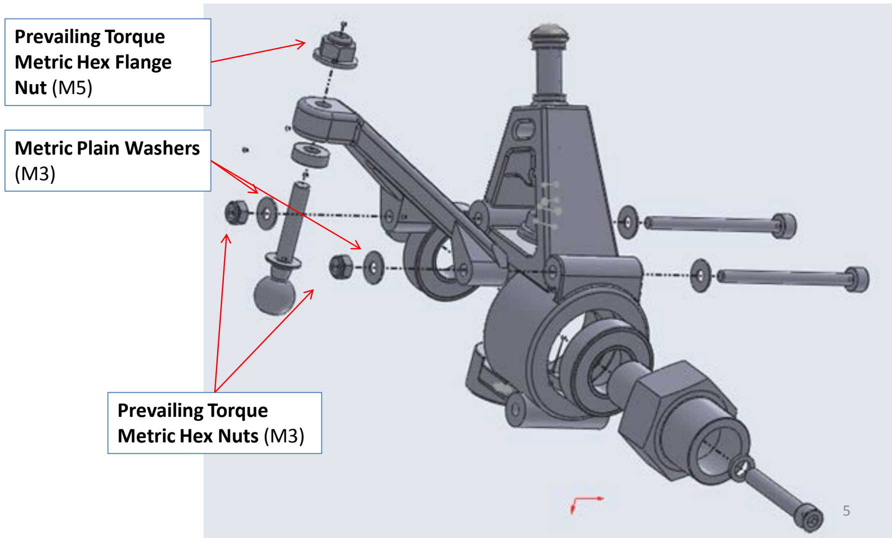
Part 1 : Assembly (Fastening) Queries
Front Hub Right Assembly



4

Part 1 : Assembly (Fastening) Queries

Front Hub Right Assembly



5

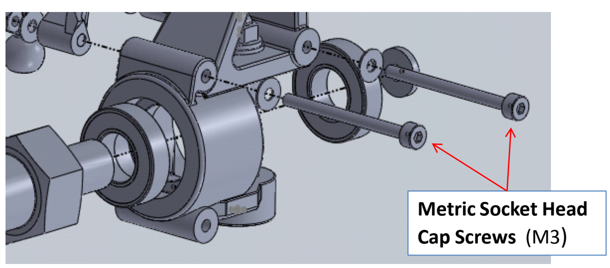
Query 1

Query 1a

What types of fastening tools can be used for operating on *Metric Socket Head Cap Screw?*

Query 1b

What types of machines can be used for these tools?



6

Query 1a (Schema Query)

- Select *Fastening Tool* in the Concept tree and specify the following criteria
  - **Fastening Tool . usedForFasteners := Metric Socket Head Cap Screw**

- **Results**
  - Hex Key (manual handheld machine/tool)
  - Hex Socket Bit (requires a machine)
  - Hex Bit (requires a machine)

7

Query 1b (Schema Query)

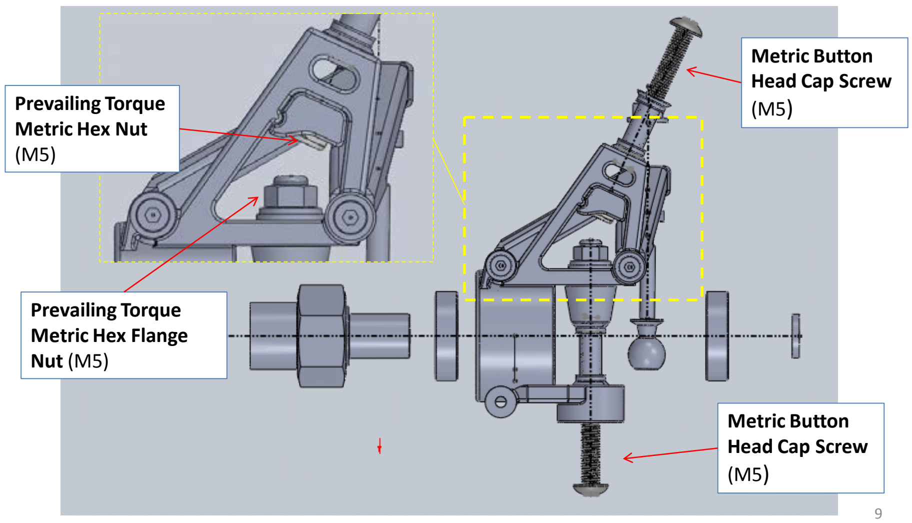
- Select *Machine* in the Concept tree and specify the following criteria
  - **Machine . installed tools := Hex Socket Bit**

- **Results**
  - Brace Type, Single Revolving Hand Grip Speeder Handle
  - Electric Impact Wrench
  - Electric Ratchet Wrench
  - Hinged Handle
  - Pneumatic Impact Wrench
  - Pneumatic Ratchet Wrench
  - Reversible Ratchet Handle
  - Sliding T-Handle
  - Spin Type Screwdriver Grip Speeder Handle
  - Torque Wrench (15 different types)

- **Select any type of machine above and see instances in the library**

8

Part 1 : Assembly (Fastening) Queries
Front Hub Right Assembly



9

Query 2

Query 2a

What types of fastening tools can be used for operating on *Prevailing Torque Metric Hex Flange Nut?*

Query 2b

What specific fastening tools/machines in my foundry can be used for operating on *Prevailing Torque Metric Hex Flange Nut* of size M5 (nominal size = 8 mm) and apply a working torque of 5.9 N-m?

10

Query 2a (Schema Query)

- Select Fastening Tool in the Concept tree and specify the following criteria
  - **Fastening Tool . usedForFasteners := Prevailing-Torque Metric Hex Flange Nut**
- **Results**
  - Adjustable Wrench
  - Combination Wrench
  - Double Head Box Wrench
  - Double Head Flare Nut Wrench
  - Double Head Open End Wrench
  - Double Head Ratcheting Box Wrench
  - Socket Wrench (requires a machine)

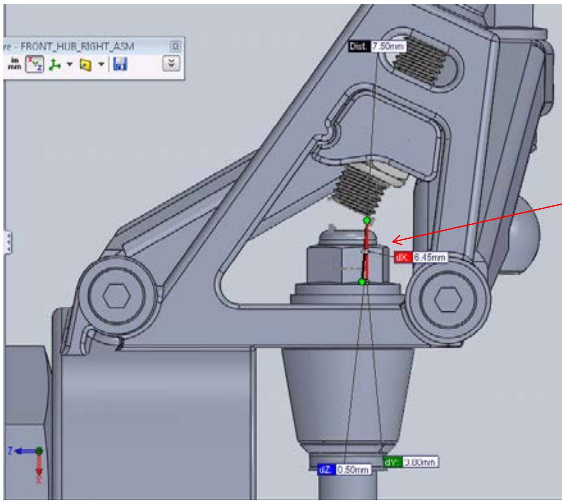
11

Query 2b (Instance Query)

- Select Fastening Tool in the Concept tree and specify the following criteria
  - Fastening Tool . usedForFasteners := Prevailing Torque Metric Hex Flange Nut
  - Fastening Tool . working torque range – max > 5.9 N-m
  - Fastening Tool . nominal size = 8 mm
- Select Fastening Machine in the Concept tree and specify the following criteria
  - Fastening Machine . installed tools:= Socket Wrench
  - Fastening Machine . working torque range – max > 5.9 N-m
  - Fastening Machine . nominal size = 8 mm
- **Results**
  - *Specific instances of fastening tools / machines*

12

Part 1 : Assembly (Fastening) Queries
Front Hub Right Assembly



Clearance parallel to axis for *Prevailing Torque Metric Hex Flange Nut:*
C = 6.45mm

13

Query 3

What specific machines/tools can be used for fastening *Prevailing Torque Metric Hex Flange Nut* and require a clearance (parallel to the fastener axis) < 6.45 mm?

14

Query 3a

- Select Fastening Tool in the Concept tree and specify the following criteria
  - Fastening Tool . usedForFasteners :=
    Prevailing Torque Metric Hex Flange Nut
  - Fastening Tool . clearance req z – parallel to fastener axis < 6.45 mm (i.e. tool requires less clearance than available)
- **Results**
  – *Specific instances of fastening tools*

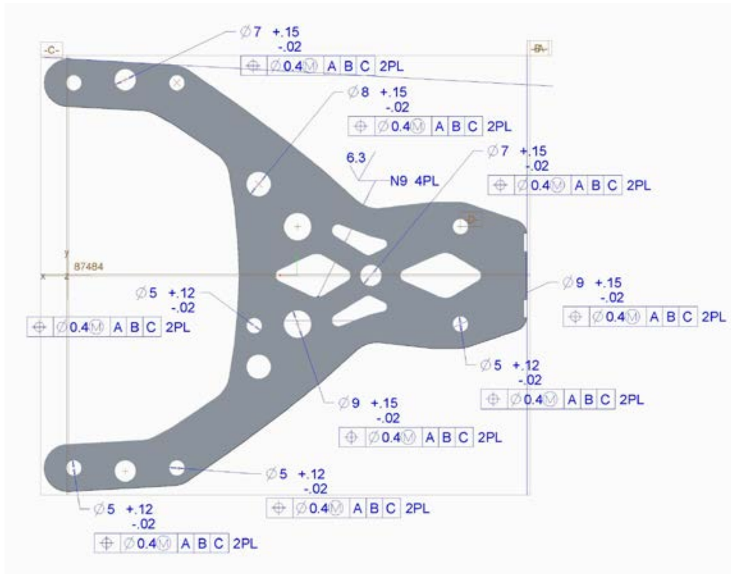
15

Query 3b

- Select Fastening Machine in the Concept tree and specify the following criteria
  - Fastening Machine . installed tools := Socket Wrench
  - Fastening Machine . wrench clearance req z – along fastener axis < 6.45 mm
- **Results**
  – *Specific instances of fastening machines*

16

Part 2 : Machining Queries



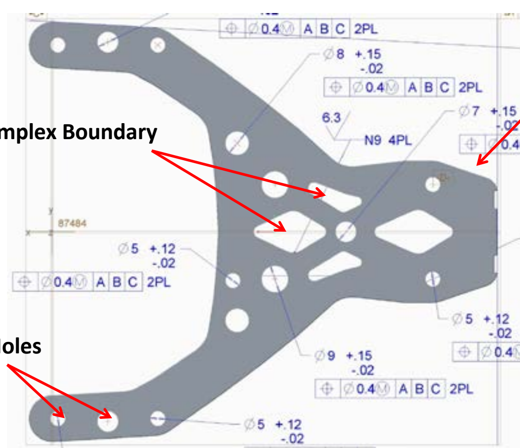
17

Query 4 - Machining

In the subject *metal* (Al 6061-T6) part, what processes can be used to produce *Through Holes, Through Complex Boundary*, and *Boundary Through Features – Complex*?

Boundary Through Feature - Complex

Through Complex Boundary



Part 102170

Through Holes

18

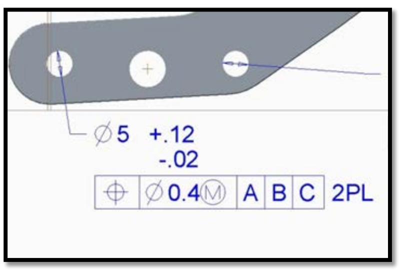
Query 4

- Select Manufacturing Process in the Concept tree and specify the following criteria
  - Process . produced features := Through Hole
  - Process . produced features := Through Complex Boundary
  - Process . Produced features := Boundary Through Feature - Complex
  - Process . allowable materials := Metal

- **Results:**
  - Abrasive Water Jet Machining
  - Laser Cutting
  - Milling
  - Punching
  - Wire EDM

19

Query 5



Assumptions (ref to Query 5)

- We have selected Milling process
- The library shows us Machining Center as a candidate machine for Milling

- What Machining Centers do I have that satisfy the following criteria?
  – Machining Center . accuracy - positioning <= 0.4mm *(Position Tolerance, at the very left bottom hole)*
  – Machining Center . observed tolerance – milling <= 0.07 mm *(Asymmetric tolerance from +0.12 to -0.02 mm is described, but we took the symmetric value)*

20

Query 5

- Select Machining Center in the concept tree and specify the following criteria:
  – Machining Center . accuracy - positioning <= 0.4
  – Machining Center . observed tolerance – milling <= 0.07
- **Results**
  – *Specific instances of Machining Center*

21

Query 6 – Facility Query

Select all facilities that have Machining Centers.

Select Facility in the Concept tree and specify the following criteria

- Facility . equipment portfolio . machines ***contains*** Machining Center

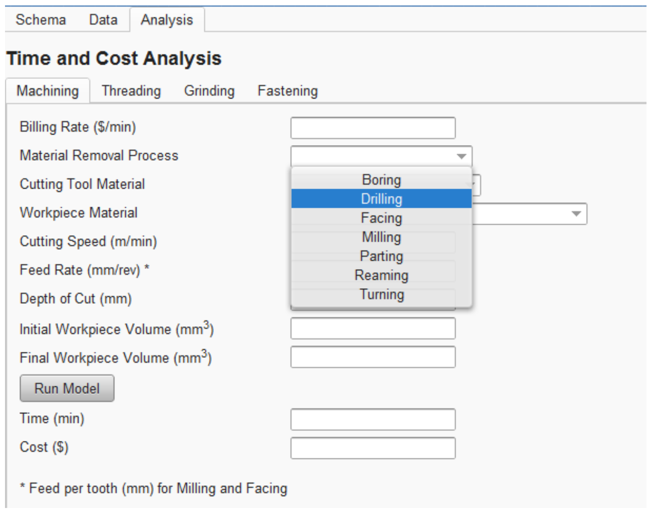
Results

- *List of facilities that contain machines of type Machining Center*

22

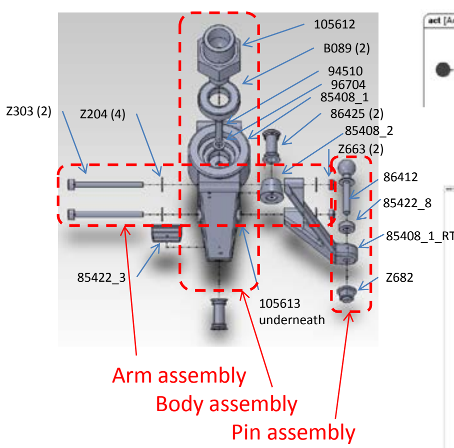
Query 7

- Demo of time and cost analysis models for unit processes

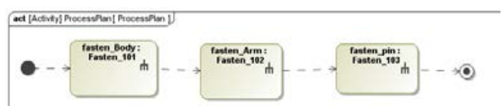


23

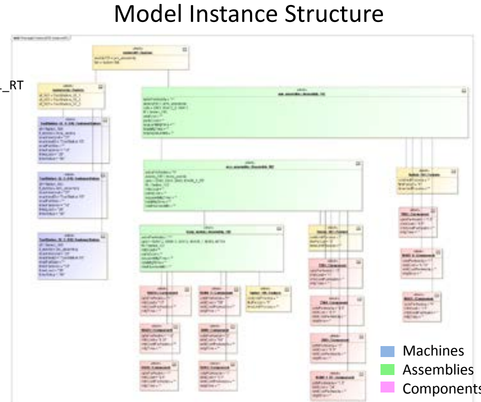
Front Hub Right Assembly



Process Plan



Model Instance Structure



Results

Assembly	Parts Cost ($)	Mfg Time (sec)	Cumul Mfg Cost ($)
Body	85.85	100	86.54
Arm	27.40	110	114.71
Pin	16.25	100	131.65

APPENDIX 6
(Task 3C Uncertainty Modeling in Manufacturing Process Planning)

This part of the report for the DARPA iFAB project covers the progress made on integrating uncertainty principles into manufacturing process planning. The first part covers a brief introduction to predictive models and their role (and importance) in engineering analysis. Thereafter, the process of eliciting uncertainty is explained (in other words, how beliefs and knowledge can be captured). An example related to predicting the cost and build time in the case of additive manufacturing processes is then discussed in more detail. Finally, the value of this work for DARPA and the benefits of integrating uncertainty principles in manufacturing process planning are presented.

Probabilistic Models

Most mathematical models in engineering are formulated in a deterministic fashion: for a set of given inputs, the model will always produce the same output. However, one must keep in mind that all models are approximations, from which can be deduced that they produce a result within an *error margin* and act under specified and assumed operating conditions. As an example, consider calculating the stiffness k of an elastic body: $k = {}^{AE}/_{l}$ (where A is the cross-sectional area, E is the elasticity modulus and l is the length). Typically, an engineer chooses specific values for each of the parameters, e.g. a length l of 8m. However, in reality, this length will almost certainly never be exactly 8m: hence, the length l is said to be *uncertain*. The source of the uncertainty in this particular case comes mainly from manufacturing and measurement limitations.

One may argue at this point that such measurement inaccuracies are already covered by *tolerances* that are specified. This is true in the sense that they act as a means to *specify* a margin for error, but do not *predict* what the actual value will be, i.e. how much a value is off from the intended value. Predictions can only be done by using principles from probability theory, hence by using probabilistic models.

Structure of Probabilistic Models

Inaccuracies related to the output of deterministic models result from two key aspects: the input parameters may already be uncertain and, as already stated, the model itself does not accurately represent the process it is inteded to describe (by definition) (this error of the model is known as the *structural error*). To make better predictions about, e.g., properties of physical objects (such as the stiffness) or the outcomes of a process plan, this uncertainty must be specified explicitly. This can be done by using random variables for the input parameters and the structural error. Figure A3.1 illustrates the general structure of mathematical models that take uncertainty into account.

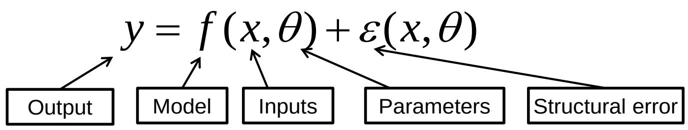


Figure A3.1: Generic structure of a model with a structural error.

Basic Types of Distributions

Probability distributions are used to describe the probabilities of different values of random variables occurring. However, before looking at how to capture the data needed to determine a probability distribution, we will briefly go over some basic aspects and types of probability distributions. This includes a description of what data needs to be elicited to quantify uncertainty.

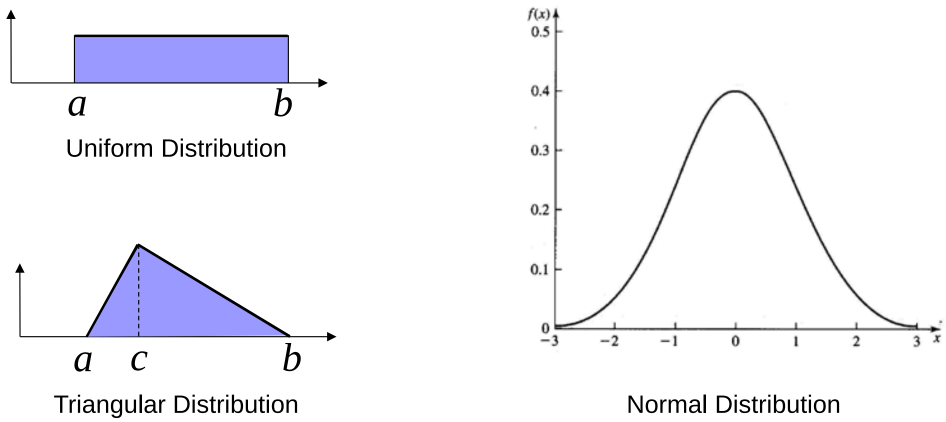


Figure A3.2: Common types of continuous distributions.

There are numerous types of probability distributions, all of which can be sorted into two basic groups: continuous and discrete distributions. Discrete distributions can only take on very specific values from a set of predefined alternative values (e.g. “red”, “black”, “blue”). These individual values may all have the same probability associated with them or completely different ones. Continuous distributions, on the other hand, can take on any real value in some specified range and include triangular, normal, beta and uniform distributions. For example, to specify a triangular distribution, one needs only three values: a minimum, a maximum and a most likely value (“mode”). For normal distributions a mean and variance is required. Uniform distributions dictate that every value within a range is equally likely (see Figure).

Uncertainty Propagation

Given a probabilistic model, one question that remains to be answered is how we perform actual calculations using uncertain parameters, i.e. random variables. The issue is that random variables cannot simply be added together. Since the output of a probabilistic model (Y) is a random variable itself, the goal is to find its probability distribution. This process is known as *uncertainty propagation*.

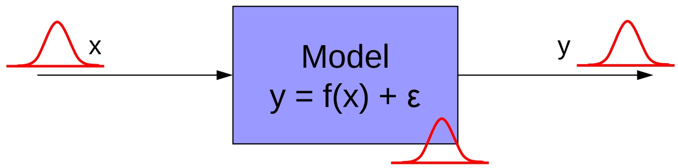


Figure A3.3: Uncertainty propagation.

One widely used method to approximate the output distribution of a probabilistic model is the use of a *Monte Carlo* simulation. A Monte Carlo simulation entails executing the given probabilistic model n times deterministically. This is done by choosing a random value for each random variable from the corresponding distributions before every deterministic execution of the model. The result of the simulation is then a set of values that represent possible outputs of the model. Using these values, a cumulative distributive function and a probability density function can be calculated.

Uncertainty Elicitation

As already mentioned, models are mere approximations of reality. Coming back to our introductory example of determining the stiffness of an elastic body, this means that while the calculated value may be 10N/m, the measured or experimentally determined value may be 10.3N/m and, when the given elastic body is produced a second time, 9.8N/m. Capturing this data for hundreds or even thousands of individual parts allows one to plot a distribution of the actual stiffness. The more data points that are collected, the better the predictions about future parts will be.

This process of collecting data is one way of quantifying uncertainty (hence determining a probability distribution). However, in situations where this is not possible, one can also elicit *beliefs* about a particular process or property. The source of these beliefs is usually an *expert*. For instance, an expert can state the lower and upper bound for the cost of a particular process (e.g. the operating cost per hour of a drilling machine) and how much it usually costs. By asking an expert to provide these three data points, one already has enough data to determine the probability density function of a triangular distribution (lower, upper bound and most likely value). In the same way one can elicit the structural error of models. Experts usually have a good idea of how well a model can determine the outcome of a particular process (e.g. cost), i.e. how "accurate" it is.

A second way of eliciting the beliefs of an expert is to ask him a series of questions that can then be used to directly determine a *cumulative distributive function* (the integral of the probability density function). To do so, an expert is asked to view the outcome of a particular process as a gamble, which pays $1 if a particular case is true and $0 otherwise. For example, in the case of determining a probability distribution for the hourly operating cost of a drilling machine, one of the many questions that could be asked is: "*How much (between $0 and $1) are you willing to bet that the hourly cost is $18 or less?*". By doing so, one can determine the beliefs through eliciting the willingness to bet. Since all bets are between 0 and 1, these bets directly represent the probability related to specific values. The resulting cumulative distributive function can then be smoothened by using nonlinear interpolation, e.g. by using a spline.

Probabilistic Cost & Time Models for Manufacturing Processes

In this section of the report, we will specifically focus on probabilistic cost and time models that are used to predict the outcome of a manufacturing process. Cost models, in particular, are known to have a large error. This dwells from the fact that cost models are commonly highly difficult to formulate and are hence complex, mainly due to the numerous different kinds of influences for different parts or products. Such errors are difficult to assess and quantify when dealing with deterministic models. Probabilistic models help capture this in a formal fashion and can help make better decisions through more accurate predictions.

Example: Additive Manufacturing

In this section we will illustrate how probabilistic models can be used to predict the cost and production time of a given manufacturing process by using additive manufacturing as an example. We will also show what information is necessary in order to use given cost and time models and how to increase the accuracy of the prediction. Additive manufacturing (as opposed to subtractive manufacturing) is a manufacturing technique where material is laid down to build a part in layers. For more information on additive manufacturing, please refer to the related literature.

Build Time Model Structure

The overall build time is estimated by the accumulation of three major contributing factors: recoating time (T_r), scanning time (T_s) and delay (T_d). Furthermore, a structural error for the cost is defined: ε_{time}.

$$T_b = T_r + T_s + T_d + \varepsilon_{buildTime} \qquad \text{(Equation 3.1)}$$

The following equations present each model:

$$L_s = floor(\frac{H_s}{LT}) \qquad \text{(Equation 3.2)}$$

$$L_p = floor(\frac{bb_z}{LT}) \qquad \text{(Equation 3.3)}$$

$$T_r = L_s \times T_{rs} + L_p \times T_{rp} \qquad \text{(Equation 3.4)}$$

$$N = (\frac{PL_x + g_x - 20}{bb_x + g_x})(\frac{PL_y + g_y - 20}{bb_y + g_y}) \qquad \text{(Equation 3.5)}$$

$$\gamma = \frac{Actual\ Volume}{Bounding\ box} \qquad \text{(Equation 3.6)}$$

$$A_{fn} = \gamma e^{\alpha(1-\gamma)} \qquad \text{(Equation 3.7)}$$

$$A_{avg} = bb_x \times bb_y \times A_{fn} \qquad \text{(Equation 3.8)}$$

$$sl = A_{avg}(\frac{n_{st} \times L_p}{hr \times d} + supfac \times \frac{L_s}{d}) \qquad \text{(Equation 3.9)}$$

$$ss_{avg} = ss_s \times sw + ss_j(1 - sw) \qquad \text{(Equation 3.10)}$$

$$T_s = \frac{N \times sl}{3600 \times ss_{avg}} \quad \text{(Equation 3.11)}$$

$$T_d = L_p\left(T_{pre} + T_{post}\right) + T_{startup} \quad \text{(Equation 3.12)}$$

Where L_s: number of layers in support, L_p: number of layers in part, T_{rs}: time to recoat in support layer, T_{rp}: time to recoat in part layer, N: number of parts on the platform, PL: platform length in plane, g: gap, bb: bounding box length, A_{fn}: area function, γ: ratio of actual volume to bounding box, α: a constant, n_{st}: number of times layer is scanned, hr: hatch spacing ratio, d: beam diameter, supfac: support structure factor, ss_{avg}: average scan speed, ss_s: part scan speed, ss_j: scan speed for moving between parts, sw: scan velocity weighting factor, T_{pre}: delay before scanning, T_{post}: delay after scanning, $T_{startup}$: startup time.

Note that for reasons of simplicity all structural errors of equations 2 to 12 are lumped into the structural error of equation 1.

Cost Model Structure

The overall cost is estimated by accumulation of four sub costs: machine purchase cost (P), machine operation cost (O), material cost (M), and labor cost (L). Furthermore, a structural error for the cost is defined: ε_{cost}.

$$Overall\ Cost = P + O + M + L + \varepsilon_{cost} \quad \text{(Equation 3.13)}$$

The following equations represent models for each of the above partial costs.

$$P = \frac{Purchase\ Cost \times T_b}{0.95 \times 24 \times 365 \times Y_{life}} \quad \text{(Equation 3.14)}$$

$$O = T_b \times C_o \quad \text{(Equation 3.15)}$$

$$M = K_s \times K_r \times N \times v \times C_m \times \rho \quad \text{(Equation 3.16)}$$

$$L = T_l \times C_l \quad \text{(Equation 3.17)}$$

Where these equations: T_b: build time (hours) see build time model below, C_o: operation rate ($), K_s: support material factor, K_r: material recycling factor, N: number of parts (see build time model), ν: part actual volume, C_m: material cost per unit mass, ρ: density.

Note that for reasons of simplicity all structural errors of equations 3.14 to 3.17 were lumped into the structural error of equation 3.13.

Uncertainty Elicitation

For all variables of the models listed in equations 3.1 to 3.17 that are not being computed and except for bb_x, bb_y, bb_z and the Actual Volume, triangular distributions were specified by a domain expert. This means that the only required input to the model is geometric information that can be extracted from a CAD tool.

During the uncertainty elicitation process, the expert (a member of Task 2) used both his expert knowledge and available historical and empirical data to construct a set of probability distributions.

It should be noted that only a very brief introduction into the basics of probability theory and the general idea behind probabilistic modeling was necessary before the elicitation process. The uncertainty was then elicited quickly and mostly indepedently. An excerpt of the elicited data is shown below:

Items	Min	Max	Likely
Purchase cost($)	9,900	1,035,000	20,618
Y_{life} (years)	5	15	7
C_o($)	990	103,500	2,062
K_s	1	10	1.5
K_r	1	10	1.5
ρ (g/cm^3)	.9	5	1.2

Example Application of the Models for the Prediction of Build Time and Cost

For demonstration purposes, the models introduced in the previous sections were implemented in Matlab®. A hypothetical geometrical model with bounding box dimensions of 20x20x10 cm and a volume of 3000 cm^3 was chosen as an input for the cost and build time models. It is assumed that only geometric information is available and that other factors such as the type of material or the additive manufacturing machine to be used has not yet been decided on. Hence, in the following results, all possible types of material included in the elicited beliefs of the domain expert are considered. For the uncertainty propagation, a Monte Carlo simulation with 1,000,000 runs was used. Figure A3.4 shows the result of the uncertainty propagation with build time plotted against cost.

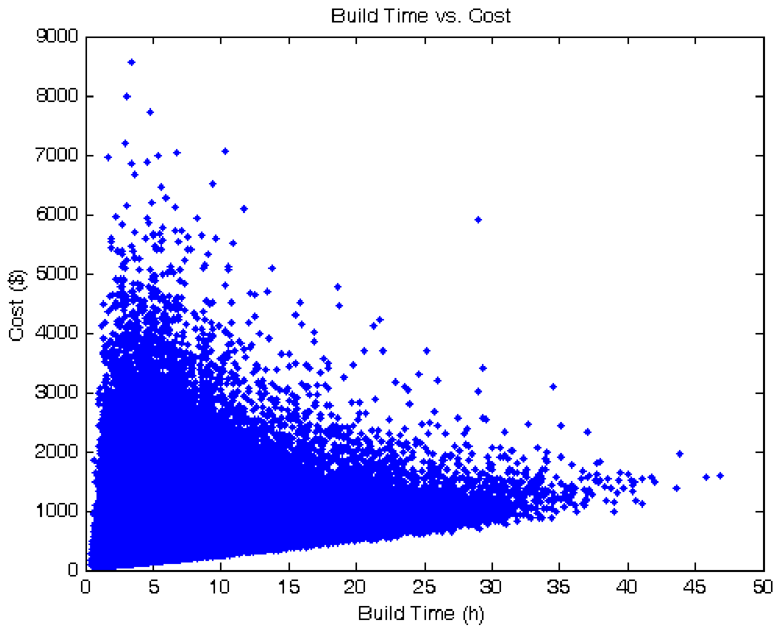


Figure A3.4: Result of the uncertainty propagation (Monte Carlo simulation with 1,000,000 runs) showing build time plotted against cost.

Figure A3.5 and Figure A3.6 show the resulting cumulative distributive function of the build time and the overall cost. Marked is also the *95th percentile*: knowing this point enables us to answer queries such as: *"Given the available information, and with a confidence of 95% (i.e. in 95% of the cases), how long will it take to build a physical model of the given geometry and how much will it cost?"*. The answer, which, in this case, would utilize the cdf's as its basis, will then be in the form of *"It will cost / take x dollars / hours or less"*.

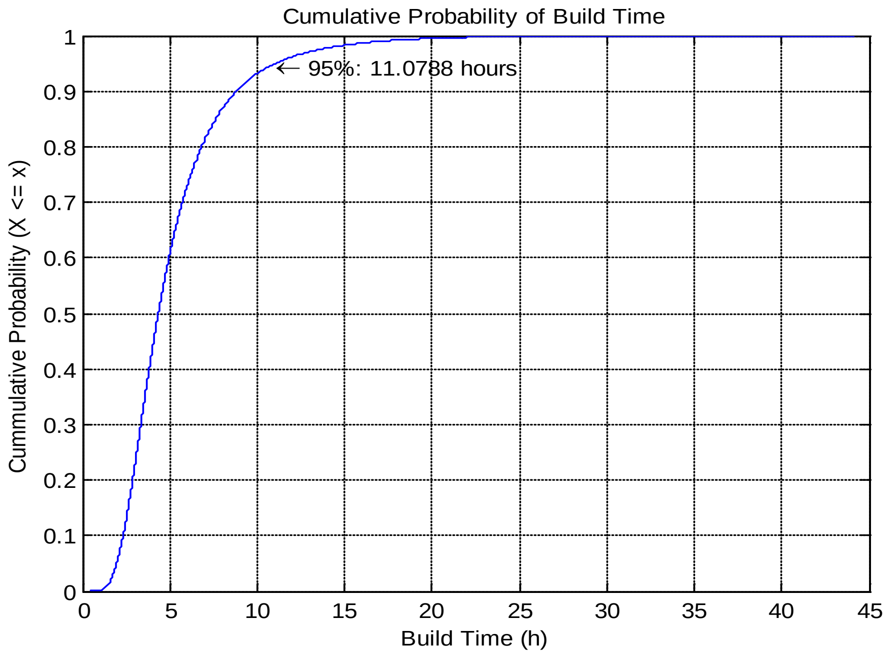


Figure A3.5: Plot of the resulting cumulative distributive function (cdf) showing the predicted build time, in hours, of a part with a volume of 3000 cm³ and a bounding box of 20 x 20 x 10 cm.

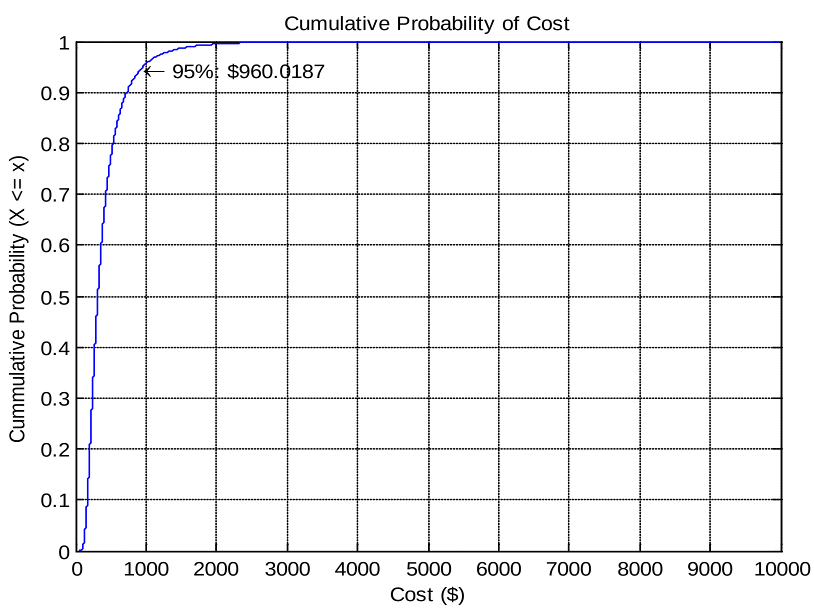


Figure A3.6: Plot of the resulting cumulative distributive function (cdf) showing the predicted cost, in dollars, of a part with a volume of 3000 cm³ and a bounding box of 20 x 20 x 10 cm.

Refining the Prediction

As stated in the previous section, the prediction is done based on *currently available data*. In the provided example for additive manufacturing, we assume that all that is given is part geometry, and that the material type and alternative machines the physical part could be produced on is not yet given. This means that we are predicting both time and cost at a relatively high level of abstraction by considering all possible types of material and machines! However, as more information is available about the manufacturing process and the part design itself, the corresponding probability distributions (or rather *beliefs*) can be updated, which will decrease the uncertainty in the output of the model. Hence, by reducing the uncertainty in the inputs, we end up with a more precise and less variant output.

Possible Extensions

In the example implementation of the models, both the bounding box and the volume of the part are assumed to be precise, deterministic values. It is assumed that these values can directly be computed by e.g. a CAD application and can be passed on without user intervention. However, these factors could also be defined to be uncertain. This would not only take into account measurement errors, but would also possibly allow for predictions to be done at levels of design where only rough geometry is available. A belief about how this geometry will evolve can then be stated to elicit the uncertainty of e.g. the eventual volume of the part.

Implementation Notes

Depending on the number of runs, uncertainty propagation using Monte Carlo simulations can be very expensive (computationally). Furthermore, such simulations involve solving each equation n times and saving the result temporarily in memory. In practice, such simulations should be run on distributed systems to achieve the maximum possible performance, especially if results are required in near real-time. If individual equations are executed on independent nodes in parallel, each computing node should process vectors of inputs and should pass results to other nodes in the form of vectors. These vectors should be the result of many individual Monte Carlo simulations executed using vector operations, i.e. a vector of random samples should be used for the inputs of the equations to be solved. This has the advantage of reducing the communication overhead within the network tremendously.

Value to DARPA & Benefits for Manufacturing Process Planning

The main benefit of integrating uncertainty principles into manufacturing process planning is that better predictions about future outcomes can be made and that these predictions are made based on knowledge that was captured previously and that can be updated at any time thereafter. This enables process planners to make better decisions about selecting a particular plan and ultimately helps in managing risk. Unlike in the case of using discrete models, uncertainty is taken into account. Part of the value for DARPA consists of being able to make better decisions and being able to predict cost and time with more confidence. Other benefits include better risk management and the ability to capture and use knowledge formally.